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TROPICAL CYCLONE MOVEMENT FORECASTS BASED ON OBSERVATIONS FROM SATELLITES

by

ROBERT W. FETT and SAMSON BRAND

JANUARY 1974

ENVIRONMENTAL PREDICTION RESEARCH FACILITY
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A method to predict 24-hr movement of tropical cyclones using consecutive daily satellite views is described. The method is based on the observation that changes in the location of major structural features of the storm are correlated with changes in the direction of movement of storm centers. Major structural features appear to retain the same relative location with respect

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to the direction of movement of the storm center. The rotation of features noted in comparing satellite views over a 24-hr period is frequently found to approximate in sense and value the further deflection the storm will take in its track during the following 24 hours. A test evaluation of the method by seven individuals using 31 separate data sets of satellite data produced results significantly better than official 24-hr forecasts.

CONTENTS

I. INTRODUCTION

Since the launch of the first meteorological satellite, TIROS I, efforts to deduce the direction of motion or to forecast the future movement of tropical cyclones on the basis of satellite data, have been largely unsuccessful. The same has held true in the use of radar for similar purposes. One reason for this lack of success may be a result of the incomplete coverage obtained by either of these systems over the length of time necessary to observe changes in storm structure associated with changes in direction of storm motion. Satellite data have been more complete in terms of coverage than radar data but, until recently, problems of format and perspective made it difficult to obtain a significant sample of cases ideally suited for such a study.

The declassification of the United States Air Force Data Acquisition and Processing Program (DAPP) provided a new source of weather satellite data which eliminated previous problems of format and perspective. This system provides fully rectified photographs on a constant scale of 1:15,000,000 or optionally, 1:7,500,000. Visual data are available at a resolution of 1/3 n mi (at subpoint) and concurrent infrared data to the same scale and for the same area are available with a resolution of 2 n mi (at subpoint). The unique display capabilities of the DAPP system provides large high quality transparent strips of these data and also provides for an infrared thresholding option which produces a vertically "sliced" infrared depiction in four shades of grey denoting different layers of the atmosphere. A complete file of DAPP data showing western North Pacific typhoons of 1972 and 1973 was recently made available to the Environmental Prediction Research Facility (EPRF). This provided an unprecedented opportunity to re-examine the question of changes in storm motion in relation to changes in cloudiness patterns.

The results of this examination suggested a method for predicting tropical cyclone motion based on satellite data which, in a test evaluation described in section 4, produced results significantly better than official 24-hr forecasts.

2. BACKGROUND

The rationale for storm structure or changes in storm structure to be related to direction of storm movement has been alluded to in the literature although not in a quantitative manner which could be of use to the operational forecaster.

In an early paper, Cline (1926) suggested that tropical cyclones should have a tendency to move toward the regions of greatest rainfall. Sherman (1953) commented on Cline's observation adding that the release of latent heat in these regions, correlating with updrafts, requires (through continuity) low-level convergence. Low-level convergence, occurring in a generally cyclonic field of motion, should lead to increased low-level vorticity in the rainy region "tending to move at least the cyclonic vorticity pattern toward the region of greatest rainfall." Sherman also noted that the hyperbolic point associated with the cyclonic indraft of the storm rotated clockwise around the storm (in the Northern Hemisphere) as the storm changed direction from westerly to northeasterly in the recurvature process. Since major asymptotes of convergence and divergence define the hyperbolic point in its association with the storm center, it seems plausible that as the storm center changes direction and the hyperbolic point shifts -- so should many of the associated patterns of storm cloudiness.

Some observational support for this hypothesis has been documented by Senn (1966) who, in a study of some 20 tropical cyclones, found that most radar patterns of storms could be loosely categorized in appearance as a "9" or a "6". He found that most westward-moving storms fitted the "9" category (with north to the top of the page) while most "6" type storms were heading north or northeast. In Figure 1, it can be seen that these numerical patterns relate well to the shape of the

cloud patterns which could be presumed to form along a convergence asymptote, assuming a cyclonic indraft embedded in flow from the east, shifting to the south and then from the west.

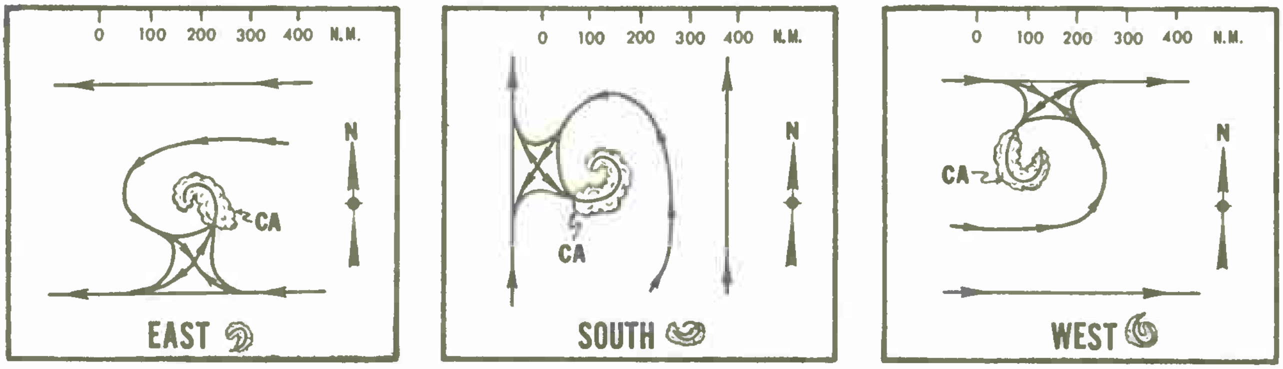

Figure 1. The rotation of the Hyperbolic Point and Convergence Asymptote (CA) associated with a tropical cyclone in a changing lower tropospheric flow from east (a), to south (b), to west (c).

Such a depiction is of course extremely over-simplified. Tropical cyclone structure can be much more complex with secondary areas of convergence including many spiral and outer-convective bands; with an eye, an upper rain and cirrus shield; and in some instances with inter-system connective cloudiness. There is also the consideration that the actual steering current need not be low-level flow or parallel to the low-level flow (as implied in Figure 1) but rather an integrated effect of flow at several levels acting to move the storm and produce the observed rotations and changes in storm direction.

Another question arises when one considers the possible use of satellite data to determine rotation of features associated with rotation of hyperbolic points. This question is, "How persistent are such features with respect to time?" Geostationary data with views approximately every half hour

are presently available only during the daylight period over the Atlantic Ocean using the ATS-3 satellite system. These data indicate preservation of many structural features for several hours. However, the rest of the world, including the more prolific areas for tropical cyclone development, is surveyed only by polar orbiting satellites at 12- to 24-hr intervals. One may question whether recognizable features can still be detected in consecutive views spaced at such intervals.

A study of cloud patterns observed on aircraft flights into Hurricane Daisy, 1958, by Malkus, Ronne and Chaffee (1961) bears on this question. Their study showed a "remarkable persistence of recognizable cloud patterns throughout the three days studied..." They found that rows of cumulonimbus, the edge of the cirrus shield, and a pronounced clearing 200 n mi southwest of the storm center, all persisted in roughly the same location relative to the storm center -- despite the passage of more than 48 hr and 200 n mi travel of the storm center.

Colon and Staff (1961), in a radar study of the same storm, noted that "... these similarities are present also when interpreted relative to the direction of motion." In fact, as discussed by Colon, a radar composite of the storm on 25 August 1958 superimposed and rotated on the composite for 27 August 1958 so that direction of motion coincided, showed excellent correspondence in the location of major echoes and bands.

If it is true that major structural features of tropical cyclones tend to rotate and maintain the same relative position with respect to the moving center, then a potential means for deducing future direction of motion exists. This idea is further developed in this paper incorporating certain assumptions concerning the tropical cyclone track over a period of 48 hr.

3. THE DEVELOPMENT OF THE METHOD

If a steering current of constant speed and constant curvature is assumed, one can obtain a depiction of tropical cyclone tracks as shown in Figure 2. This figure is an idealized depiction of tropical cyclone tracks with storm centers undergoing continuous changes in direction under the influence of steering currents of constant speed and constant curvature. T_1, T_2, and T_3 are progressive 24-hr positions of the storm centers. Small arrows indicate the tracks of the storm centers. Each 24-hr track is actually a segment of

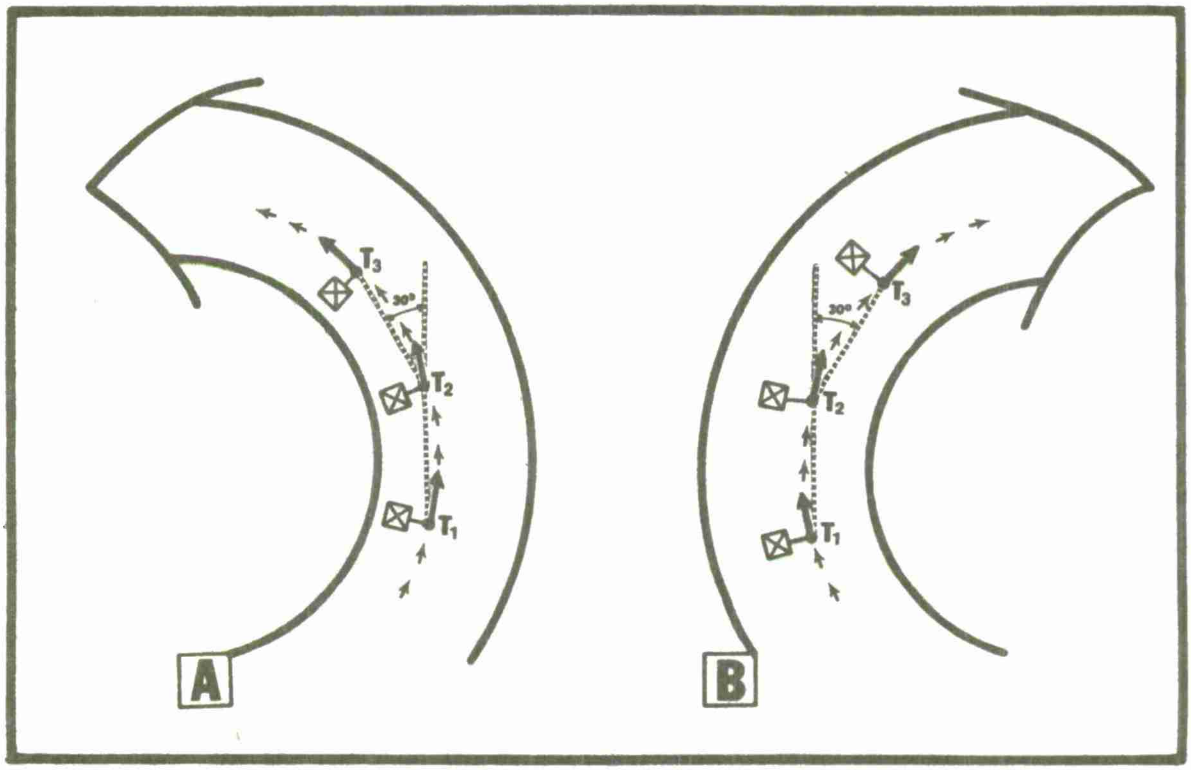

Figure 2. Idealized depiction of the movement of a tropical cyclone in a cyclonic (A) and anticyclonic (B) steering current of constant speed and constant curvature. T_1, T_2, and T_3 are progressive 24-hr positions of the storm centers. Small arrows indicate the storm track. Larger arrows are instantaneous velocity vectors. Boxed X's indicate hyperbolic points. Broad double-lined arrows indicate the flow of the steering current.

a large circle whose center is defined by the perpendicular bisectors of T_1T_2, and T_2T_3. Large arrows indicate the instantaneous motion of the storm centers at points along the track. Hyperbolic points perpendicular to the instantaneous velocity vectors (indicative of steering currents parallel to the instantaneous velocity vectors) are denoted by boxed X's. In Figure 2A the tropical cyclone changes direction counterclockwise by 30 degrees in transit from T_1 to T_2. A 24-hr persistence of curvature forecast from time T_2 would require the storm center to be deflected another 30 degrees and to be located at position T_3. The distance traveled is such that $T_1T_2 = T_2T_3$. Figure 2B, similarly, shows the case for a storm being steered in a clockwise manner.

If one knew the location of the hyperbolic point at 24-hr positions T_1 and T_2 in relation to the storm center, one could measure the relative angular rotation of this feature and use this as a persistence forecast for continued turning during the next 24 hr. Alternately, if no rotation were noted, straight-line extrapolation in direction T_1T_2 would probably be the best forecast. Unfortunately, weather reconnaissance data are seldom available or sufficient to permit accurate location of the hyperbolic point in relation to the storm center. The same information, however, may be available indirectly through an examination of satellite photographs.

When one compares consecutive daily satellite views of a tropical cyclone, a striking similarity in appearance is generally noted. The similarity is especially pronounced if storm intensity has remained fairly stable during the 24-hr period. Even some rather drastic changes in intensity do not entirely destroy the resemblance of characteristics from one day to the next. This can be seen quite clearly if one compares the view of Tropical Storm Anita on 6 July 1973

(Figure 3), intensity 35 kt, with the following day's view (Figure 4), intensity 60 kt. Note in particular the asymmetry of the storm's center position with respect to major overcast cloudiness west of the storm center on both days, the noticeable spiral bands curving into the storm from the north on both days, and the general overall shape of cloudiness west of the storm center which persists from one day to the next. If the outline of these major features and surrounding convective cloudiness associated with Anita on 6 July are traced onto a plastic overlay (Figure 5) and then this overlay is superimposed over Anita on 7 July (rotating so as to achieve a "best-fit") the depiction shown in Figure 6 is obtained. As can be seen, a counterclockwise rotation of the overlay by about 30 degrees was necessary to obtain this fit. If this rotation is indeed related to a similar change in the position of the hyperbolic point relative to the storm center; and if such a tendency for continued rotation were assumed to persist for the following 24 hr with no change in the speed or curvature of the steering current; then a deflection of the storm of 30 degrees to the left of its past 24-hr track would be anticipated to a position as shown in Figure 7 (see also Figure 2A). In Figure 7 the dashed line shows the previous 24-hr track of Anita and the predicted future course deviating 30 degrees to the left. Anita's predicted center position is shown by the small arrow. The verification of this concept is shown in Figures 8 and 9 which show Anita on 8 July. As can be seen, the forecast course actually bisects the eye of the storm on this date and the predicted center falls within the actual eye of the storm.

In examining many of the DAPP typhoon views available it was found that there were certain characteristic changes which were useful in determining the amount of rotation occurring in the 24-hr period from "day 1" to "day 2."

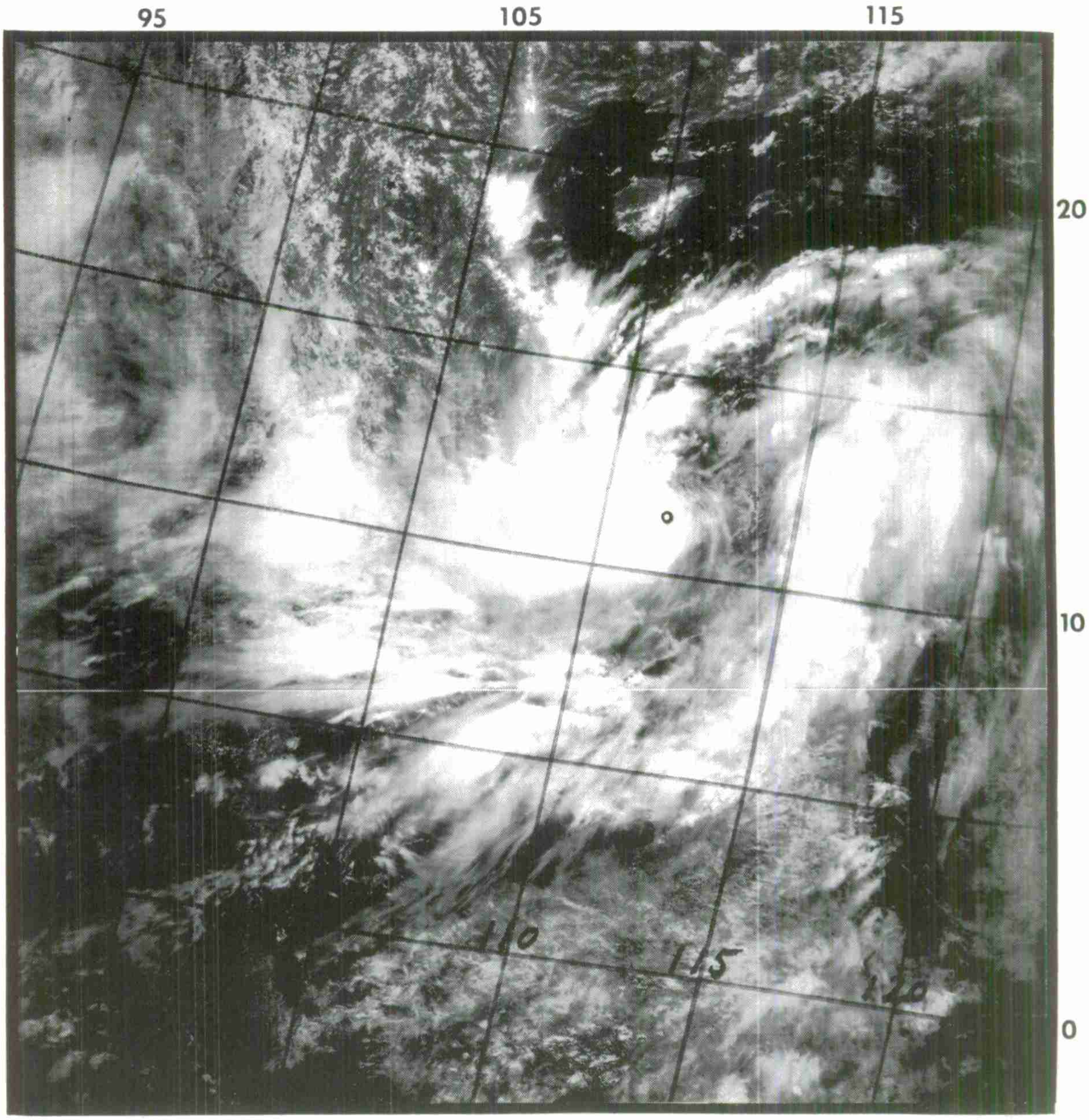

Figure 3. Tropical Storm Anita on 6 July 1973, 0500 GMT (maximum wind, 35 kt). Approximate position of the storm's center is indicated by the small circle.

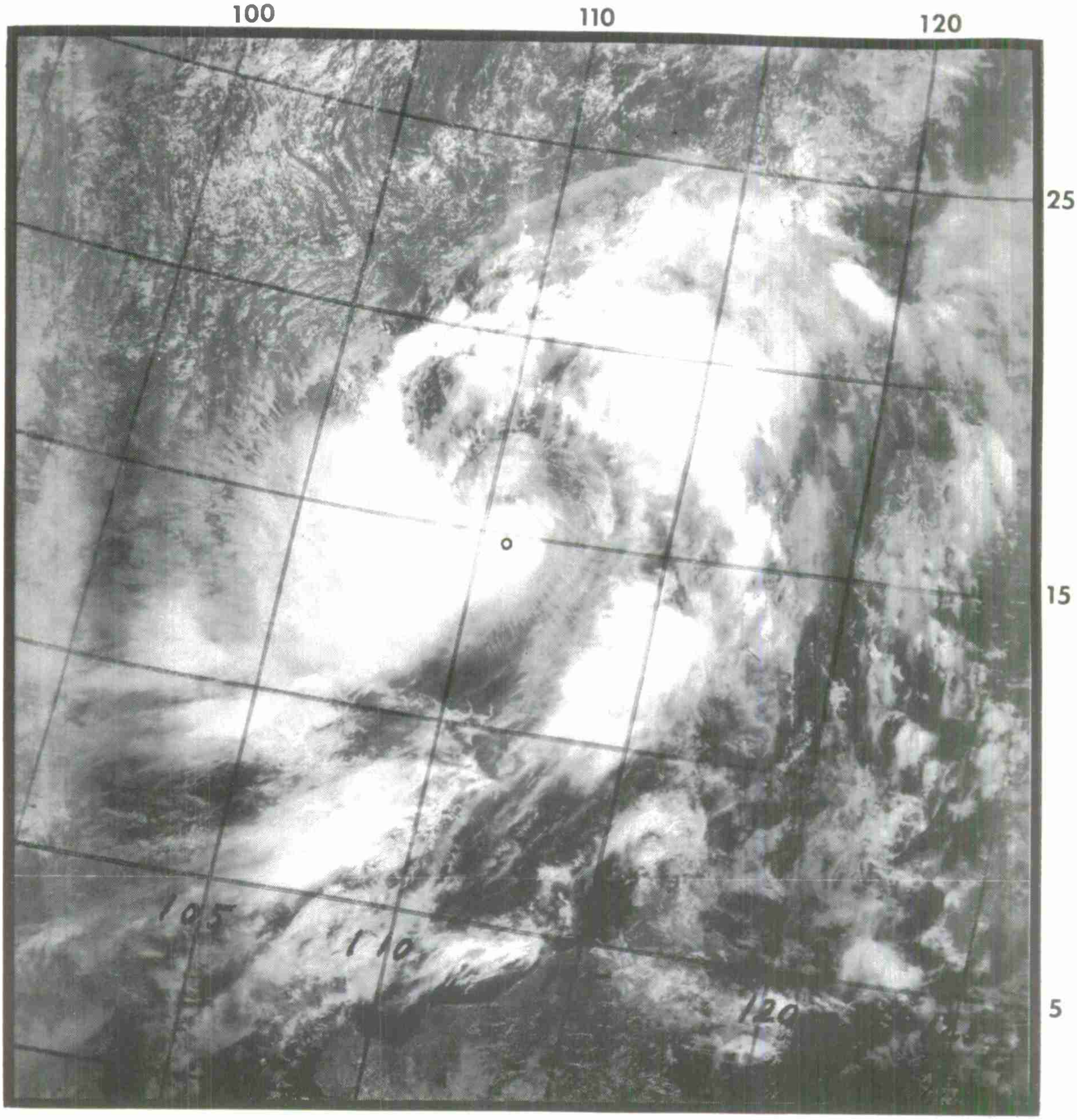

Figure 4. Tropical Storm Anita on 7 July 1973, 0446 GMT (maximum wind, 60 kt). Approximate position of the storm's center is indicated by the small circle.

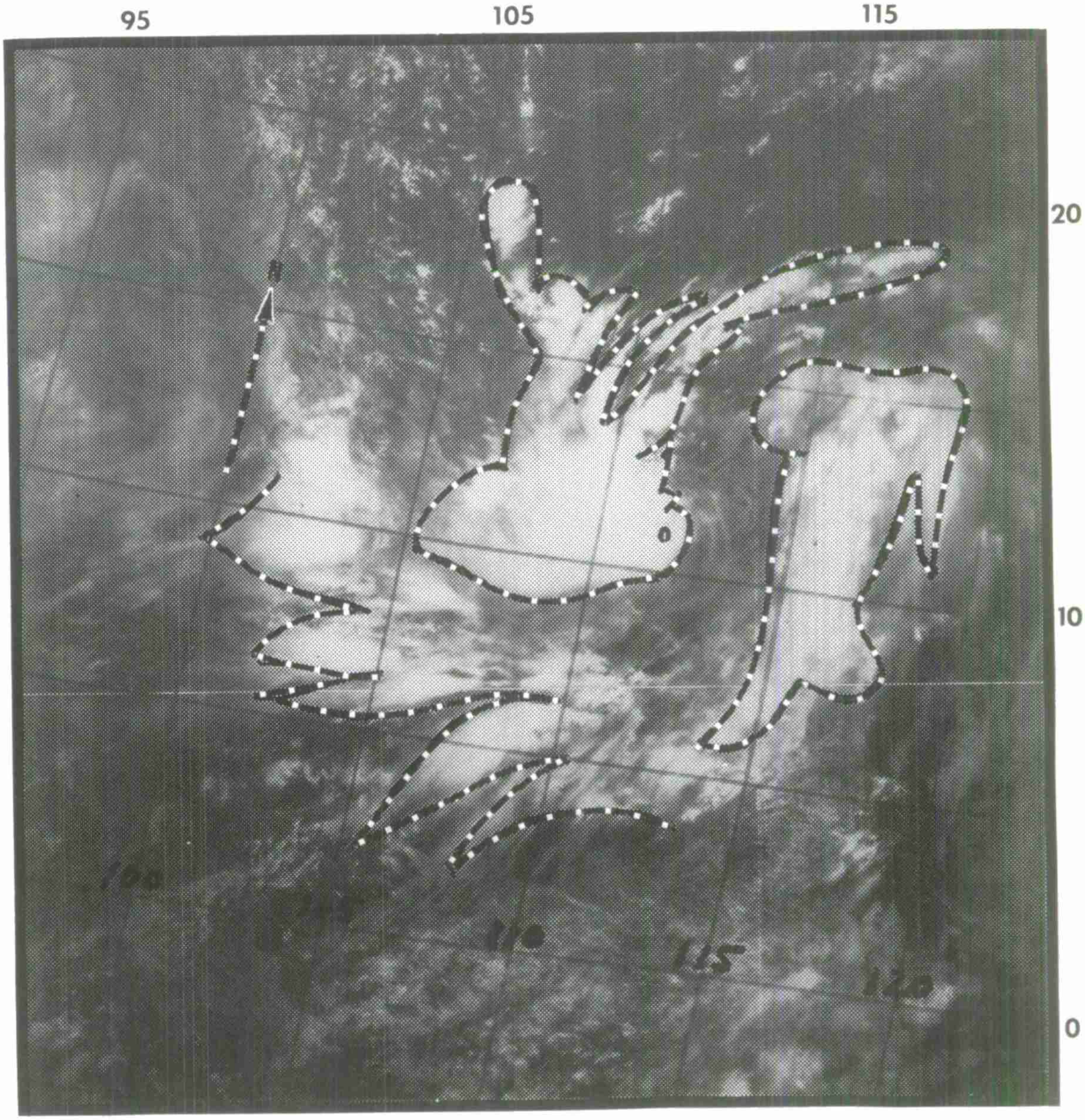

Figure 5. Outline of major cloud features of Tropical Storm Anita on 6 July 1973, 0500 GMT.

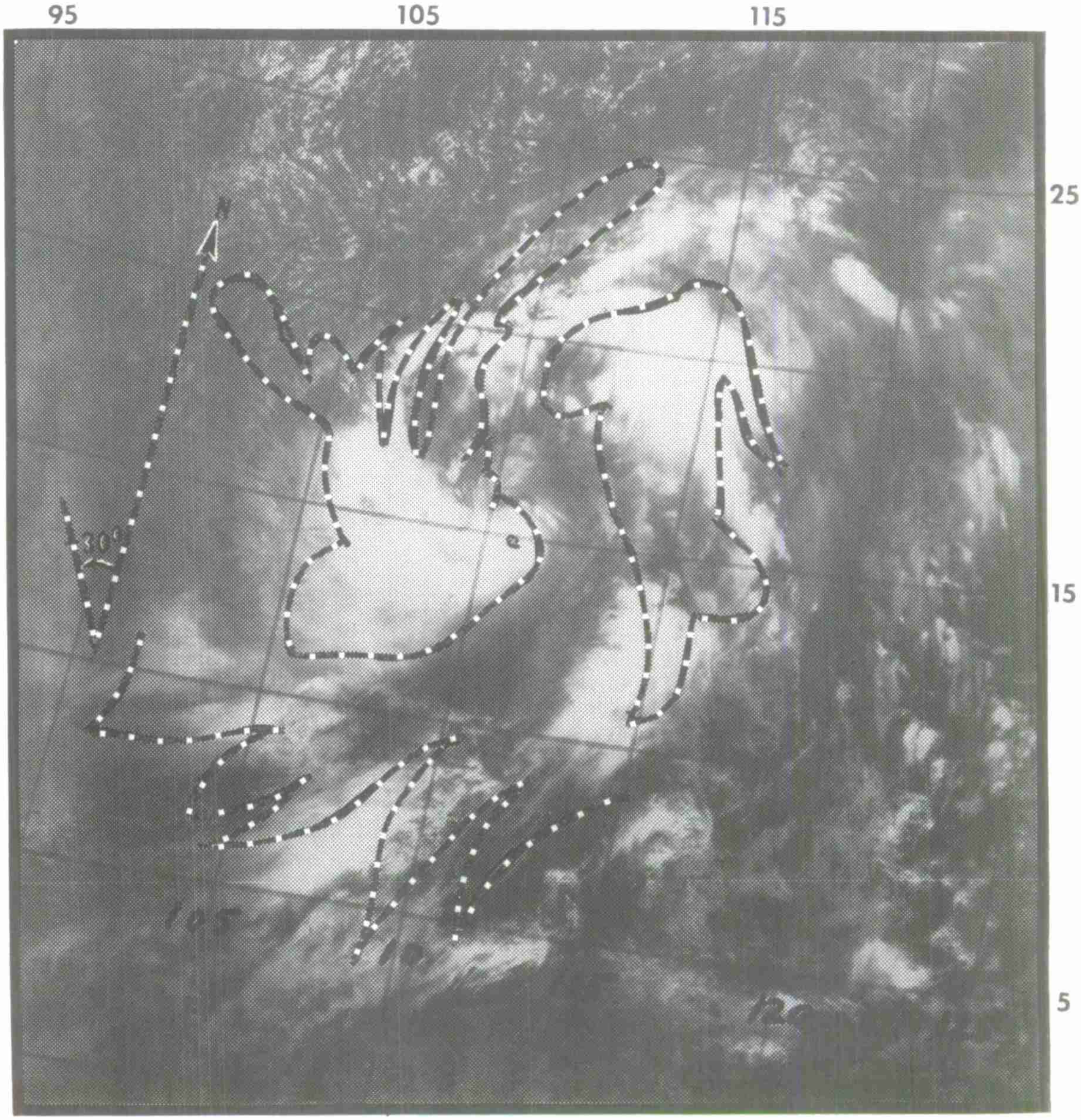

Figure 6. Outline of major cloud features of Tropical Storm Anita on 6 July 1973, 0500 GMT superimposed over Anita on 7 July 1973, 0446 GMT so as to achieve a "best fit."

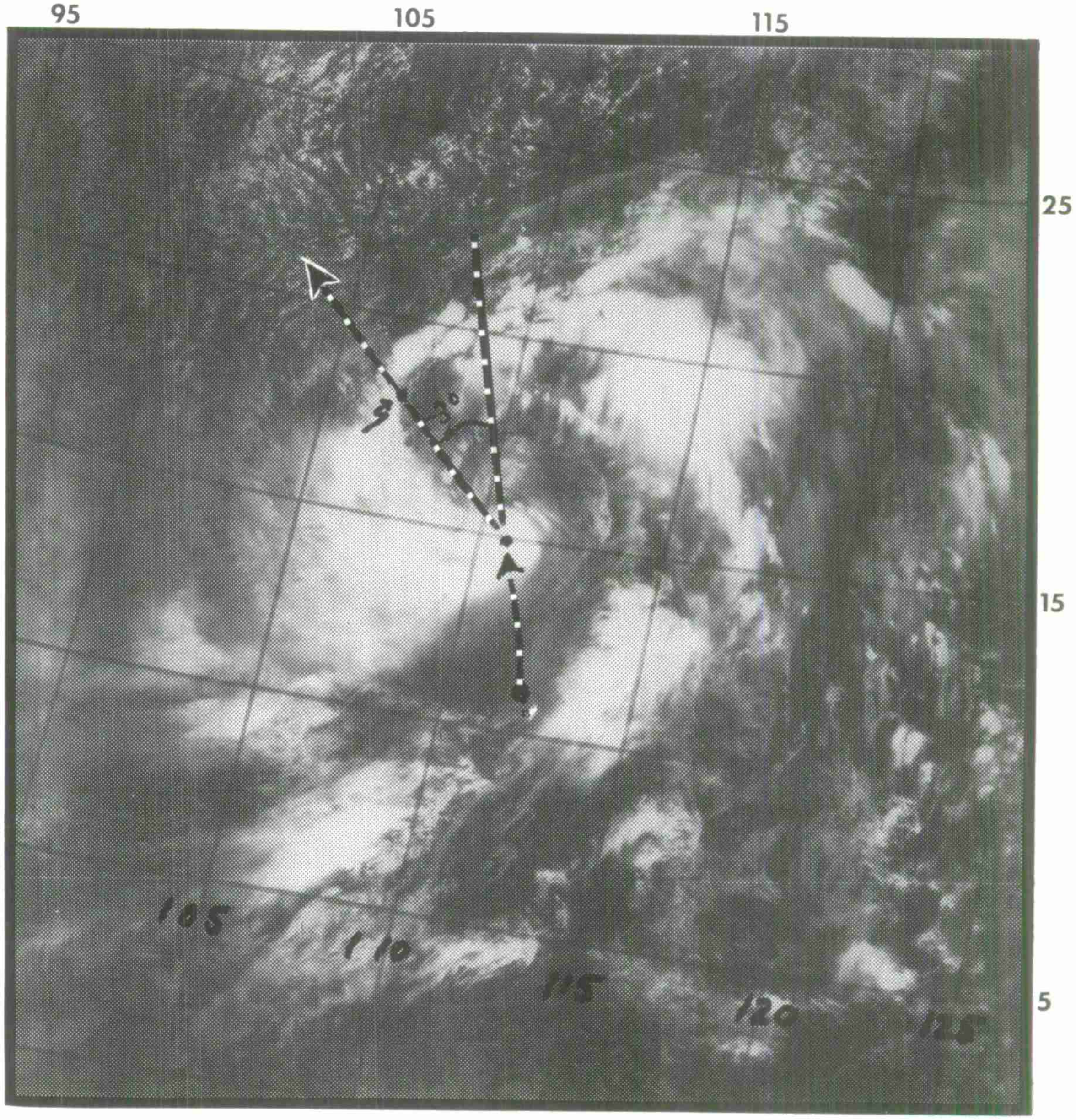

Figure 7. Predicted 24-hr position of Tropical Storm Anita (small arrow). Past 24-hr position of Anita is indicated near 11N, 112E.

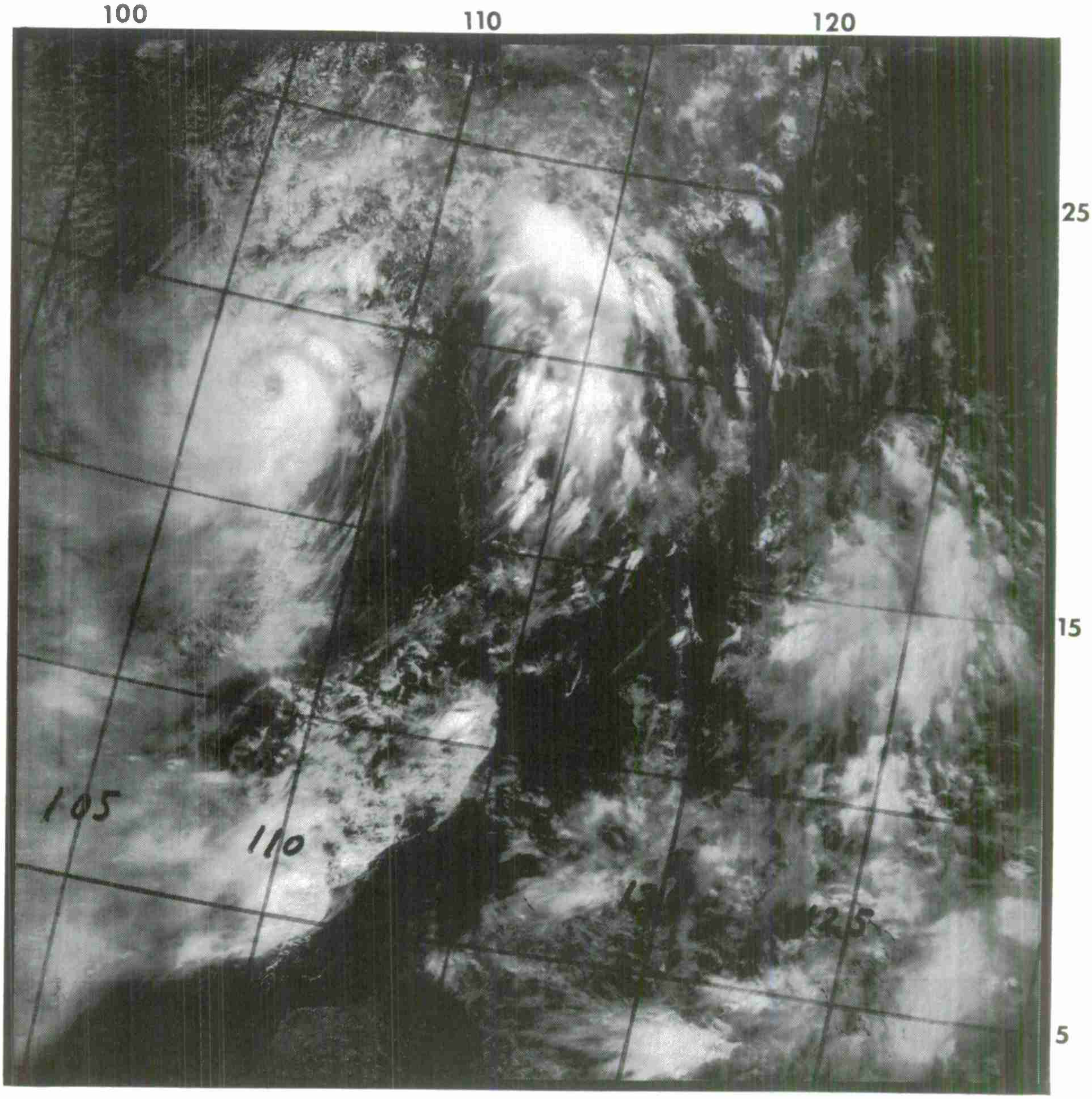

Figure 8. Typhoon Anita on 8 July 1973, 0431 GMT.

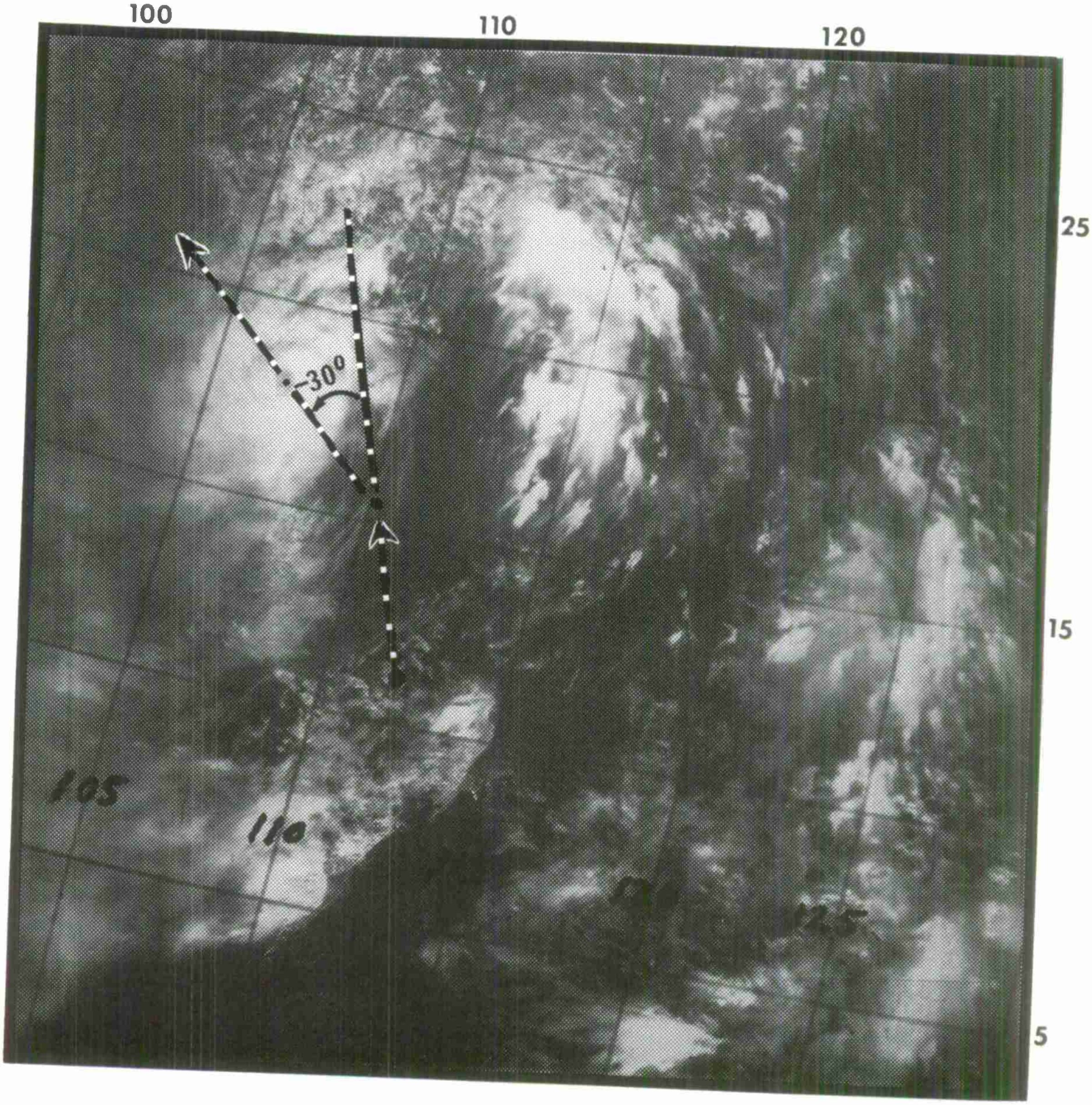

Figure 9. Typhoon Anita on 8 July 1973, 0431 GMT. Past 24-hr and 48-hr positions of Anita are indicated near 15.5N, 110E, and 11N, 112E, respectively.

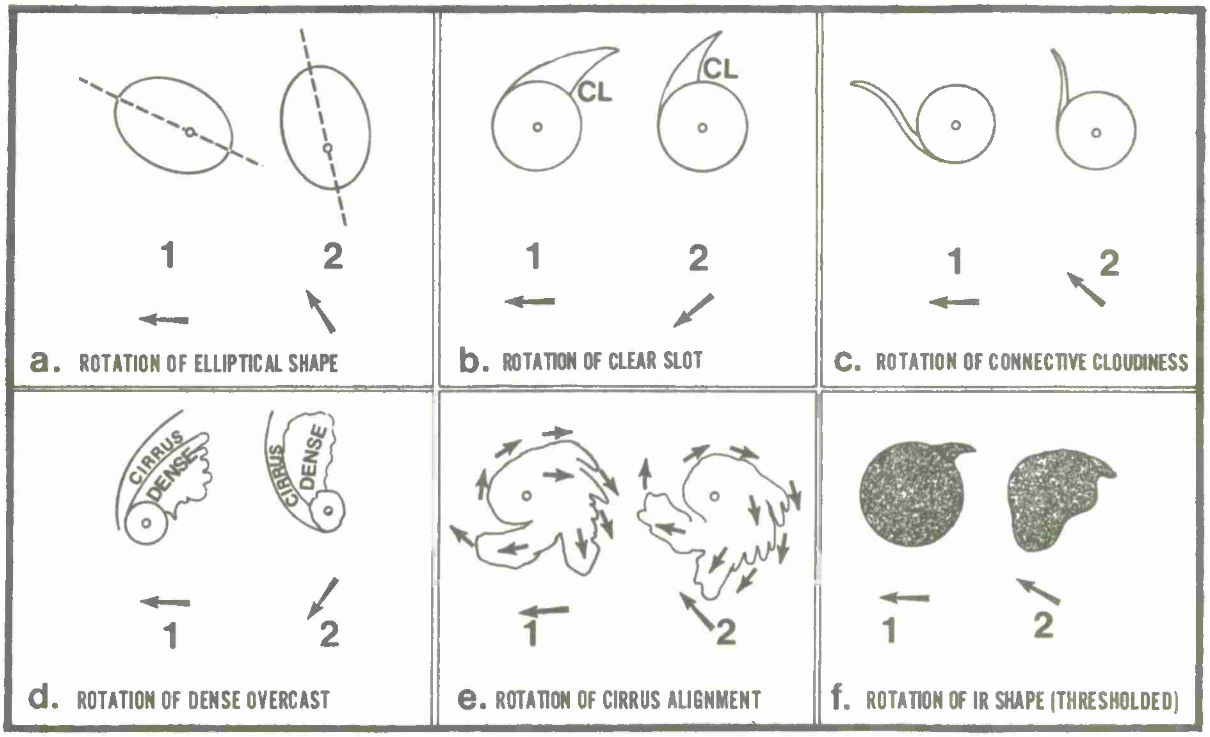

Figure 10. Characteristic changes in cloud patterns associated with directional changes of motion of tropical cyclones.

Figure 10 is a schematic showing some of these changes. The general shape of the storm system (Figure 10a) is often elliptical. In this case by rotating the shape or axis of the ellipse on "day 1" so that it coincides with the axis on "day 2" a positive (clockwise) deflection can be noted. In Figure 10a, for example, a deflection of the storm to the right by about 50 degrees would be anticipated in the following 24-hr (verifying at day 3). Figures 11 and 12 show how use of this characteristic pattern rotation would have produced an almost perfect forecast for deducing a sudden 65-degree deflection to the left of the past 24-hr track for Typhoon Rita during the period 19-20 July 1972 (see also typhoon track diagram, Figure 13).

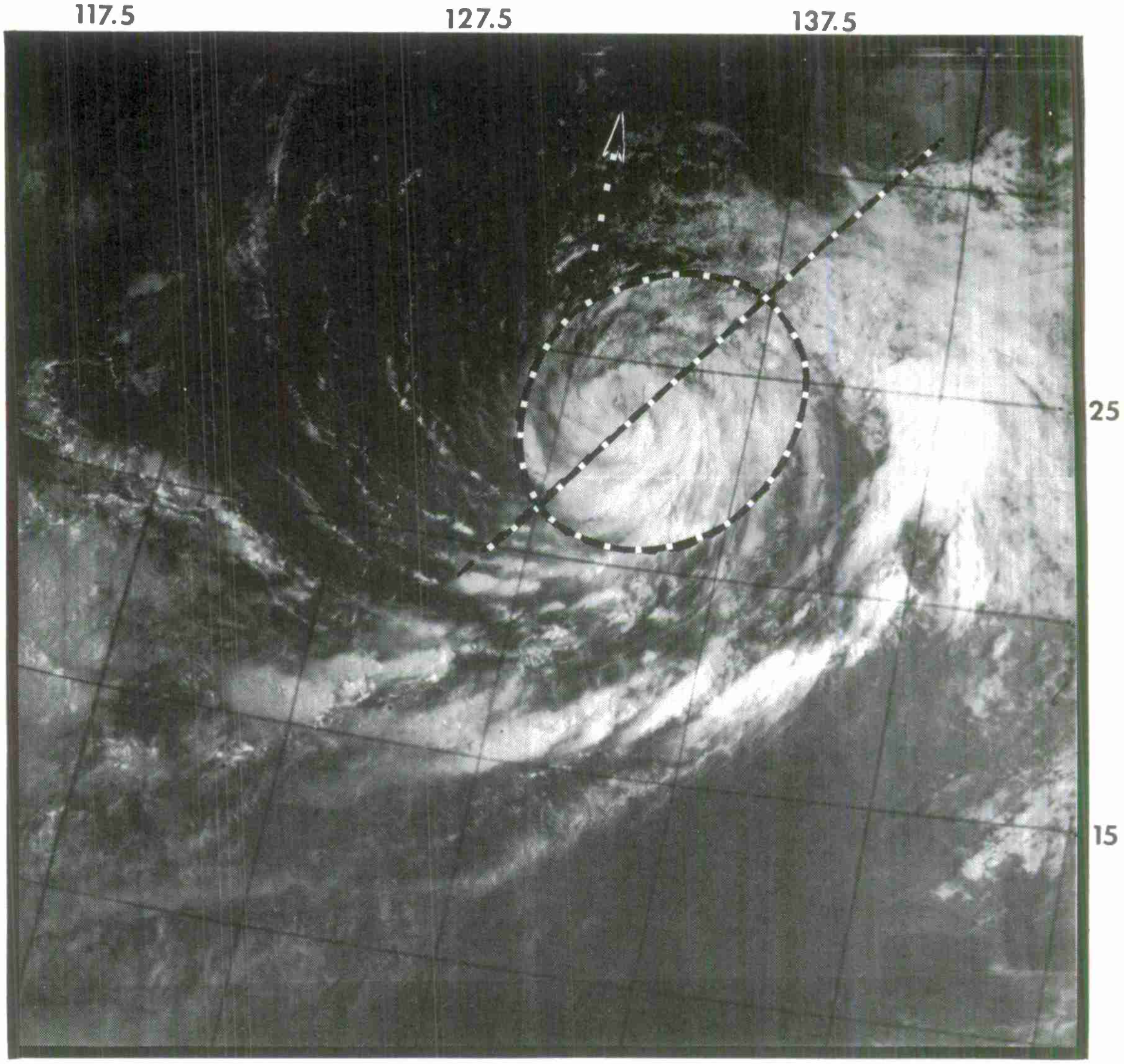

Figure 11. Typhoon Rita on 17 July 1972, 2305 GMT. Maximum surface winds - 70 kt. The elliptical shape and its major axis passing near the storm center are indicated by the stippled curve and line.

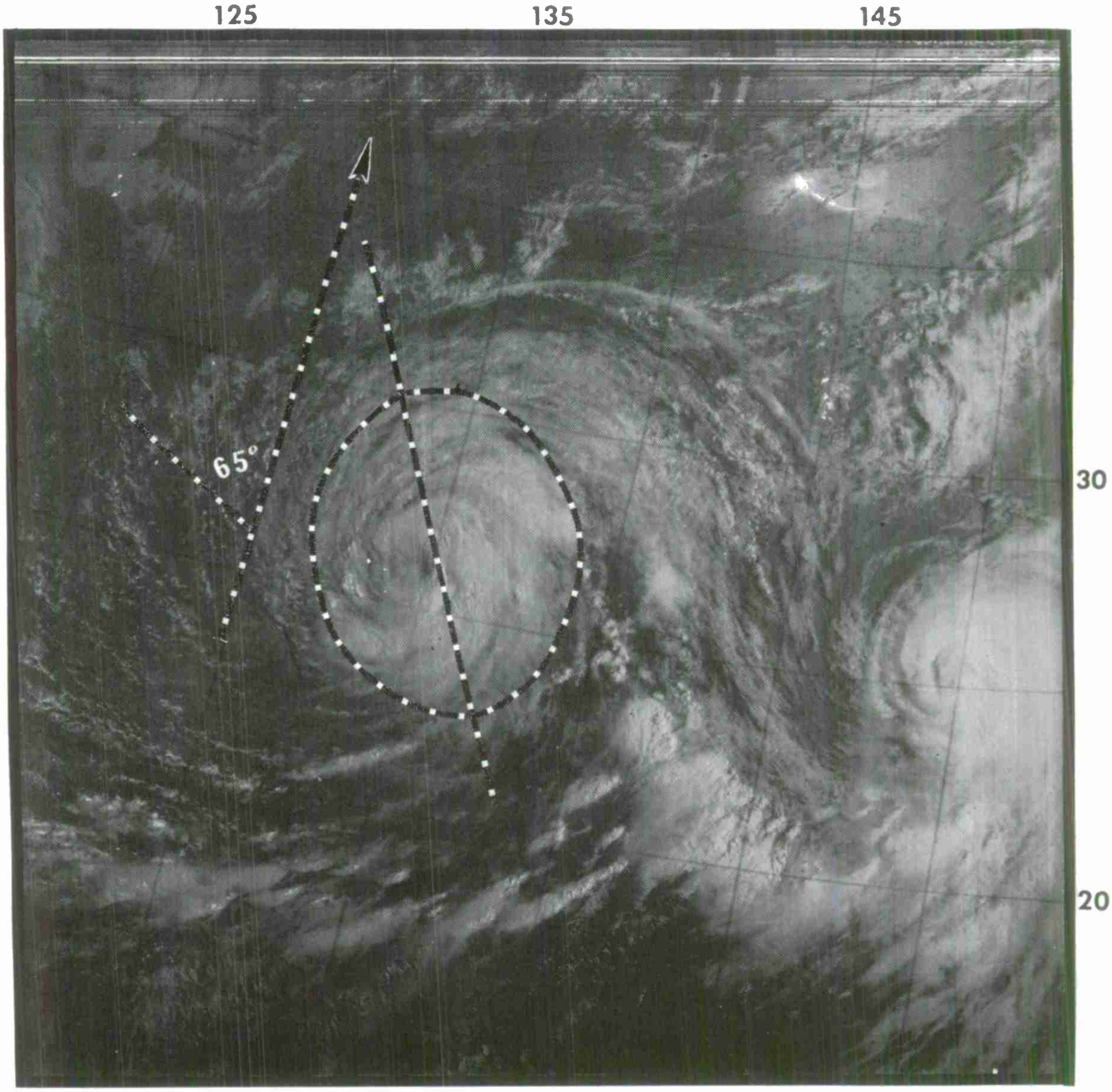

Figure 12. Typhoon Rita on 18 July 1972, 2238 GMT. Maximum surface winds - 85 kt. The elliptical shape and its major axis shown in stippling from Figure 11 have been superimposed and rotated in this depiction by 65° to obtain a "best-fit."

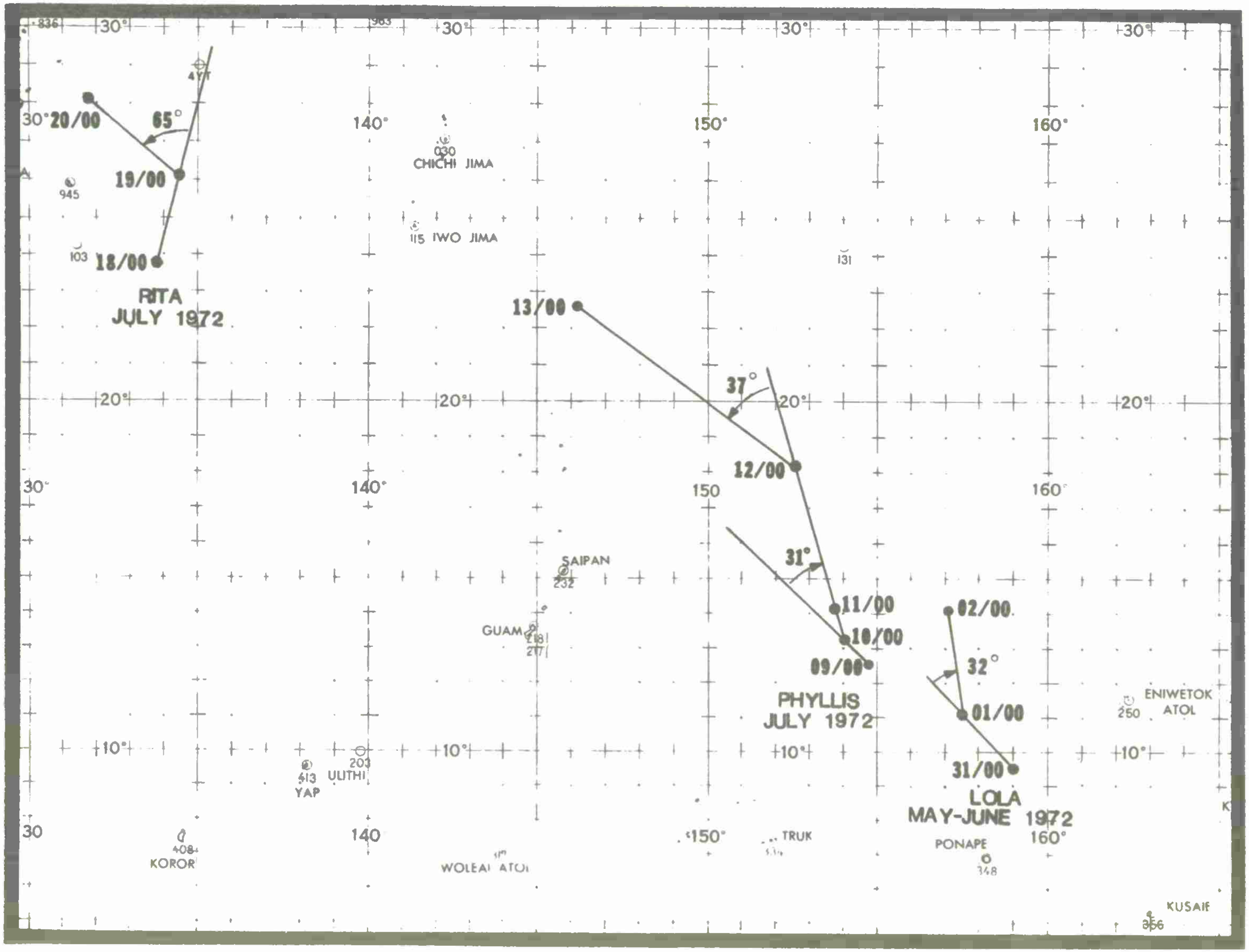

Figure 13. Selected best track positions and angular deflections from previous 24-hr straight-line tracks for Typhoons Rita, Phyllis and Lola (1972 Annual Typhoon Report).

Clear areas or clear slots are often noted (Figure 10b) which apparently rotate as the storm changes direction. Analysis of rotation in Figure 10b indicates that the storm should be forecast to deflect approximately 35 degrees to the left in the 24-hr period following day 2.

A 50 degree shift to the right (Figure 10C) can be deduced by noting the clockwise rotation of connective banding leading into this model depiction. Such banding is frequently found along a convergence asymptote leading from one storm to another and can consist either of convective bands or bands of cirrus. Figures 14 and 15 show two consecutive daily views of Tropical Cyclone Phyllis during the period 2200 GMT, 8 July 1972, to 2140 GMT, 9 July 1972. The key to forecasting the 31-degree deflection to the right, as shown in Figure 13, for the following 24-hr period consisted of taking the overlay from Figure 14, superimposing this on Figure 15, and obtaining a best fit through matching 1) the edge of the main overcast disk, 2) the alignment of the convective band leading from Phyllis southeast toward Tropical Storm Tess, and 3) the alignment of the clear slot between the outer convective band and the main body of Phyllis.

The edge of the main overcast cloud shield surrounding the storm and the rotation of the shape of this edge is perhaps the most important single element to consider in attempting to determine sense and value of rotation (see Figure 10d). Normally, a thin cirrus shield extends beyond the edge of the main overcast disk and parallels the curvature of this feature. Figures 16 and 17 showing Typhoon Phyllis at 2112 GMT on 10 July 1972, and at 2227 GMT on 11 July 1972, exemplify this characteristic. A best fit matching of the overlay drawn on Figure 16 with the cloud features of the storm as shown on Figure 17, using the cirrus edge and the main dense overcast edge as a guide, resulted in a rotation of about 39 degrees to the left. This agrees within a couple of degrees of the actual storm motion during the subsequent 24-hr period (see Figure 13).

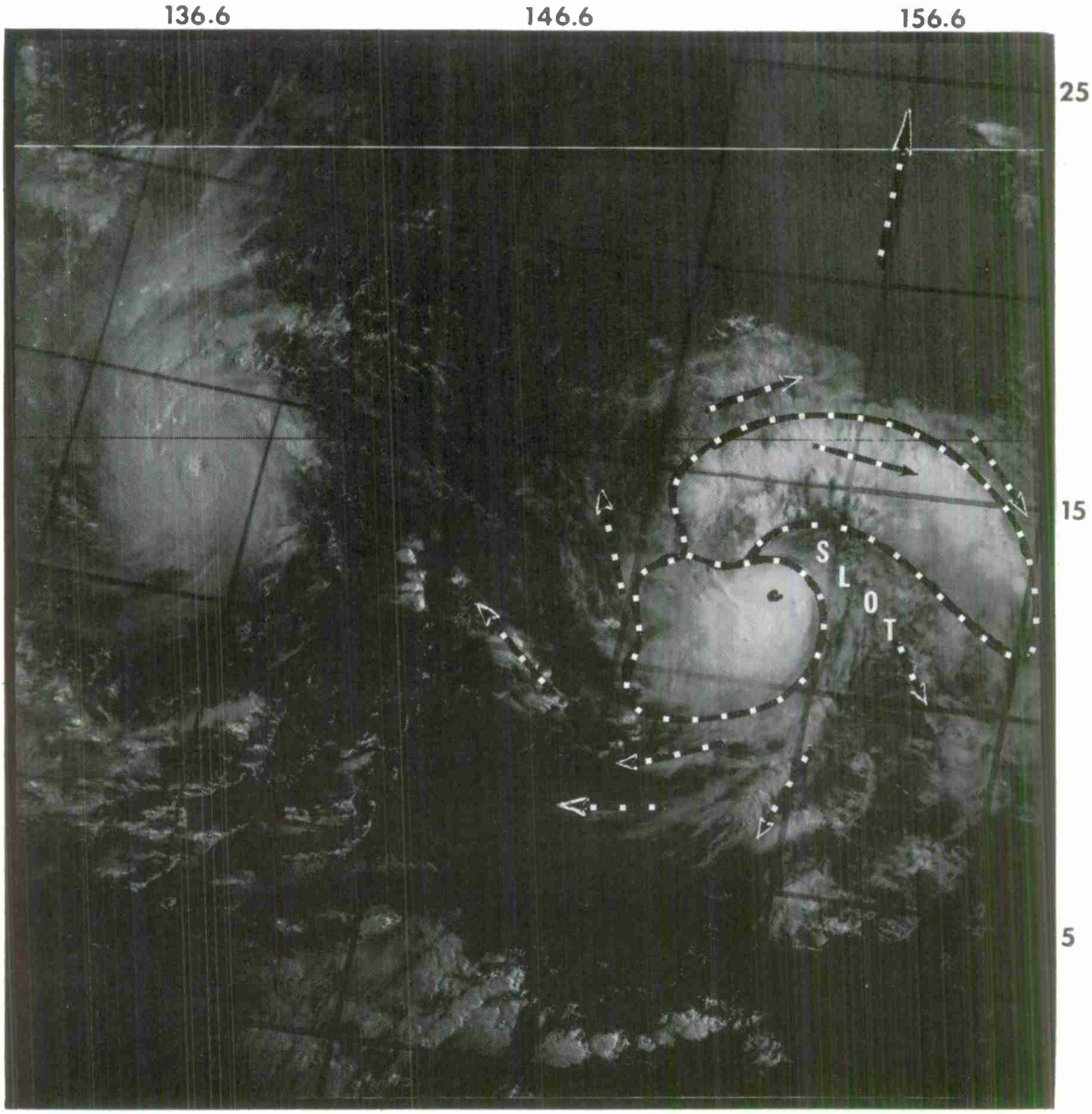

Figure 14. Tropical Storm Phyllis on 8 July 1972, 2200 GMT. Maximum surface winds - 60 kt. Typhoon Rita is visible to the west.

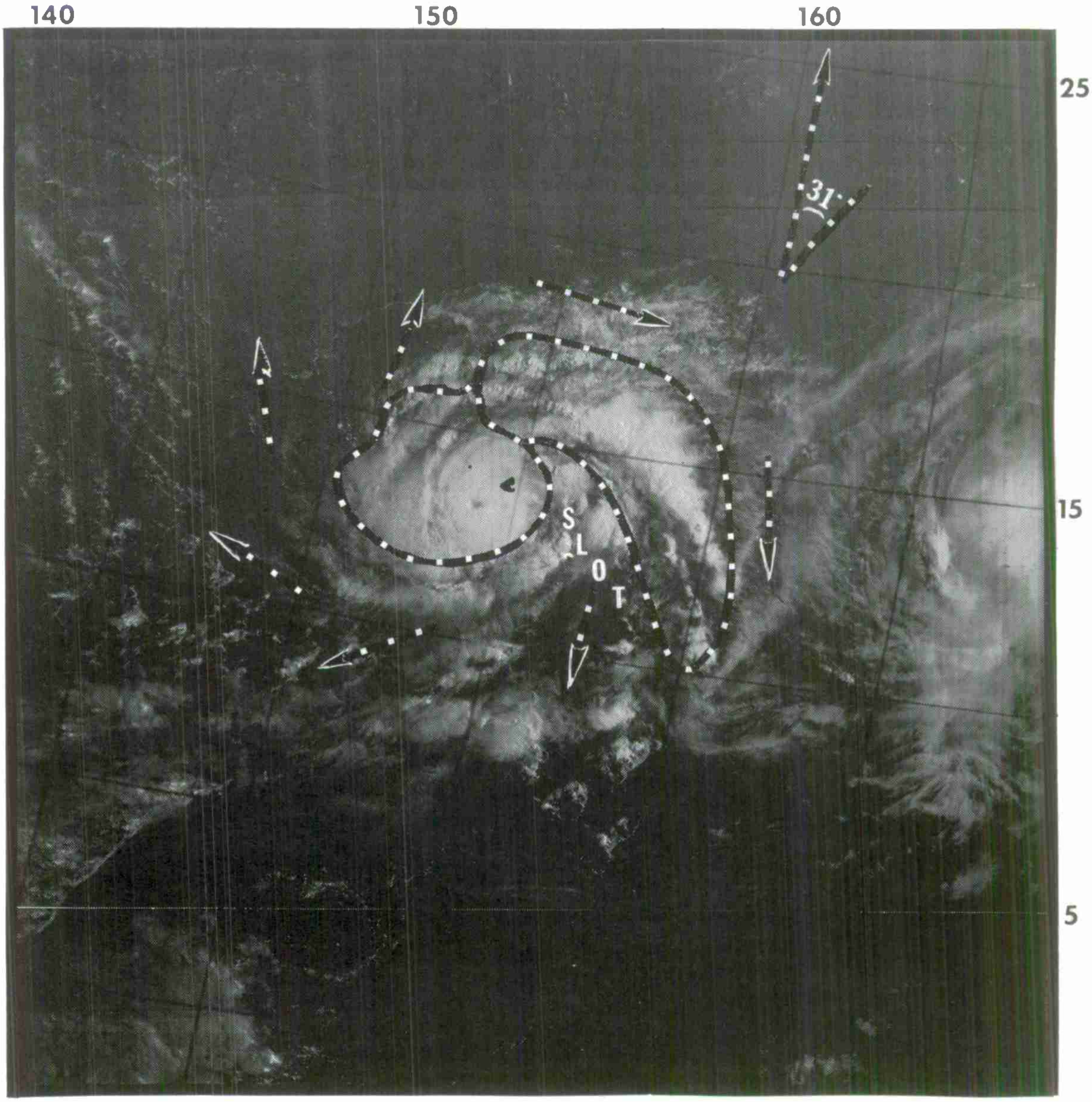

Figure 15. Typhoon Phyllis on 9 July 1972, 2140 GMT. Maximum surface winds - 85 kt. Tropical Storm Tess is visible to the east.

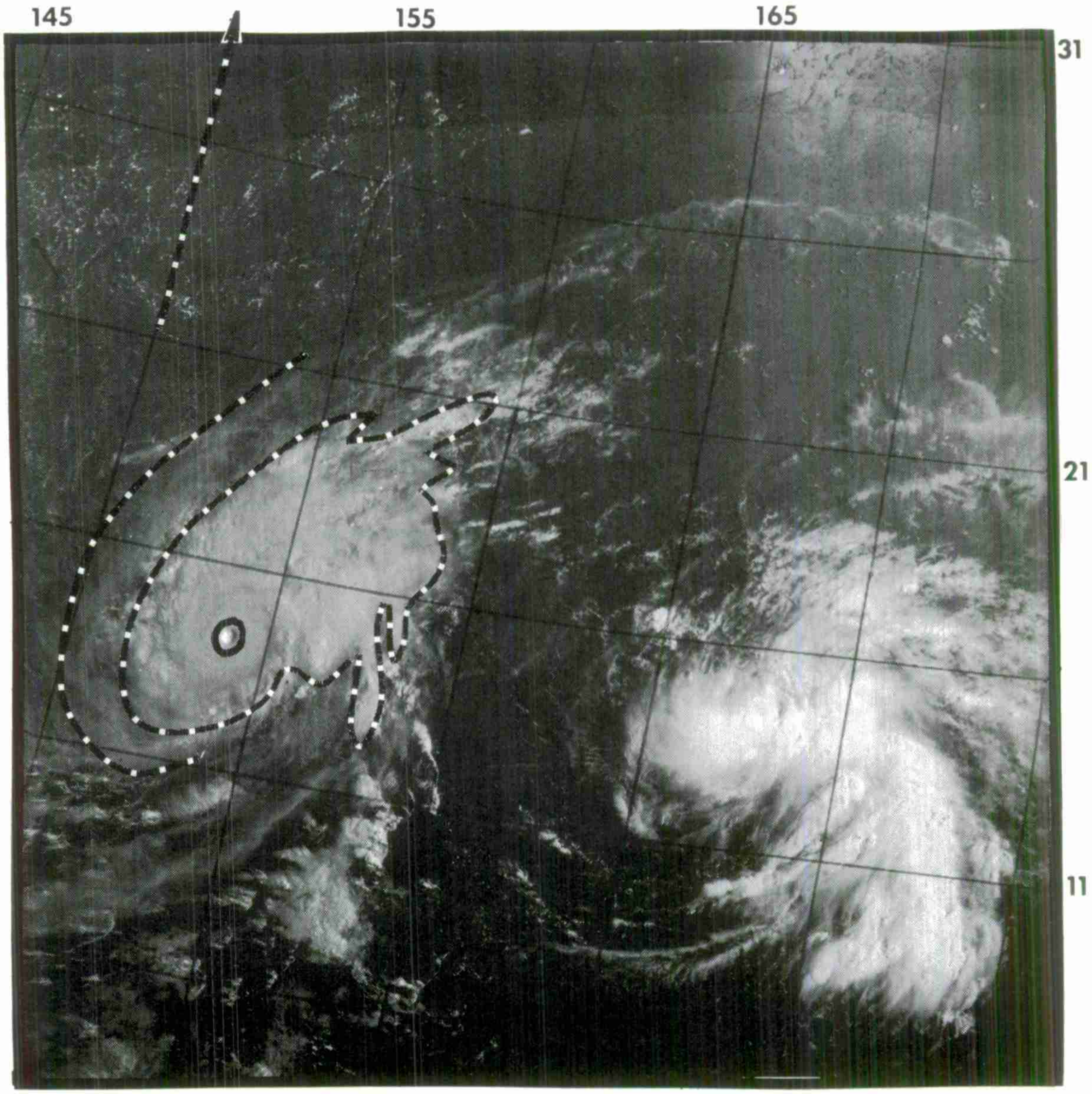

Figure 16. Typhoon Phyllis on 10 July 1972, 2112 GMT. Maximum winds - 115 kt. Tropical Storm Tess is visible to the east.

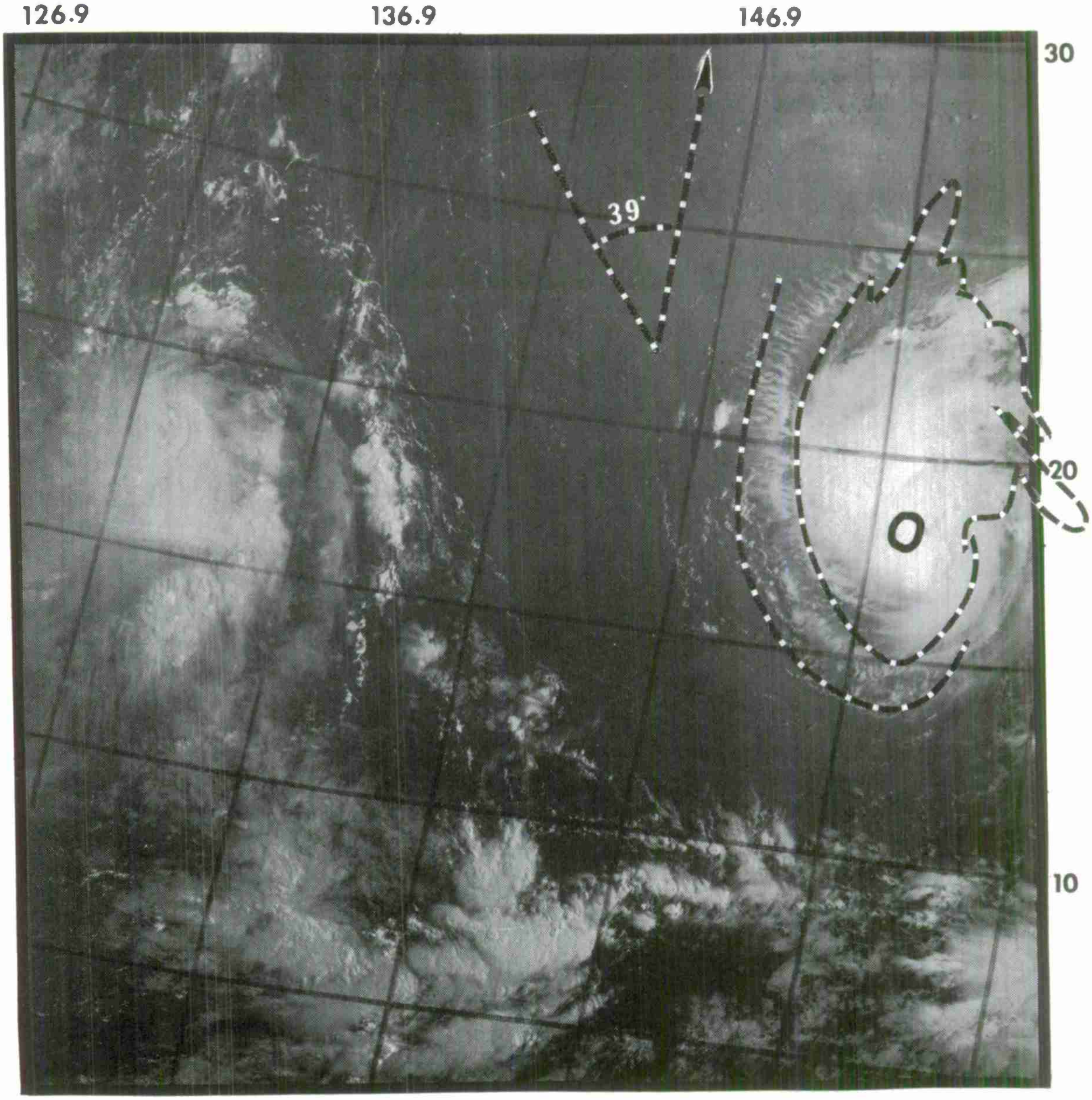

Figure 17. Typhoon Phyllis on 11 July 1972, 2227 GMT. Maximum surface winds - 105 kt. Typhoon Rita is visible to the west.

Another important point which may be derived from this example is that features close to the center of the storm should be given highest priority in attempting to achieve a "best-fit." The eye of the storm as drawn on the overlay (day 1) need not exactly correspond with the location of the eye on day 2. However, it should be held within a degree or two of this feature. Cirrus striations and convective features further away from the storm must be given secondary priority to matching features intimately associated with the storm's immediate environment. In other words if matching secondary features results in a mis-match of the main storm outline, such secondary indicators must be disregarded.

As might have been anticipated, much was learned during the course of the test evaluation which was not available to the examinees but is now considered important in retrospect. One of the most important of these was the use of arrows paralleling detected cirrus striations indicative of the upper-level flow (normally anticyclonic) above the storm area (Figure 10e). By supplementing the outline of major storm features with these indicators of upper-level flow, and rotating them until they parallel the upper-level flow on the following day's picture, it is often possible to improve the resultant derived rotation. The upper-level flow indicators appear to perform the function of "fine-tuning" to achieve the "best-fit." Such indicators must always be used as secondary indicators once major structural features have been matched to the highest degree possible. Figures 18 and 19 show how effectively such a method worked in a depiction of Typhoon Lola on 31 May-1 June 1972. The flow indicators suggested more clockwise turning than might have been deduced from structural features alone. The suggested 30-degree deflection to the right corresponded very nicely with the actual deflection of 32 degrees (see Figure 13).

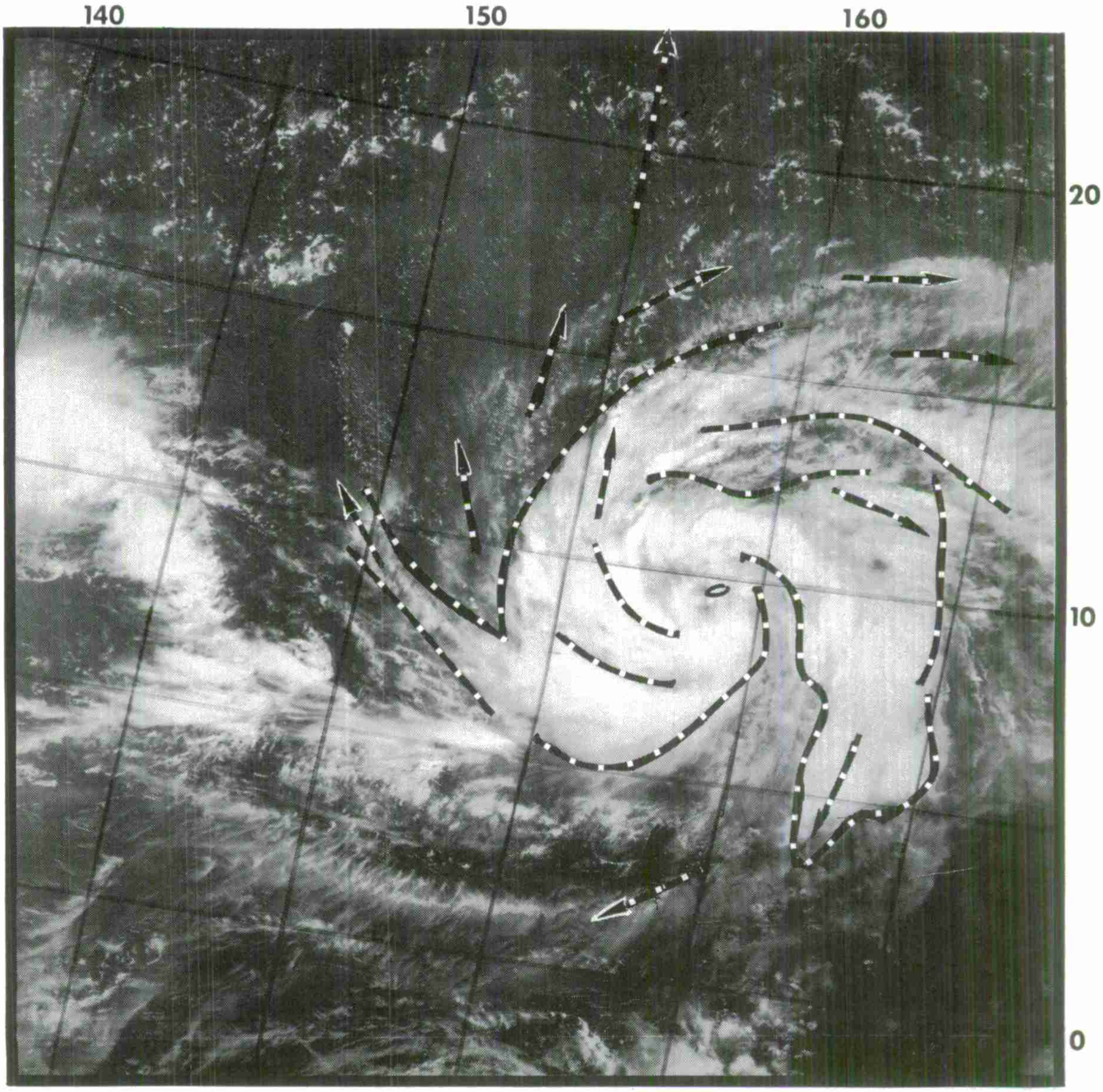

Figure 18. Tropical Storm Lola on 31 May 1972, 0158 GMT. Maximum surface winds - 60 kt. Arrows indicate probable direction of upper-level flow deduced from cirrus striations.

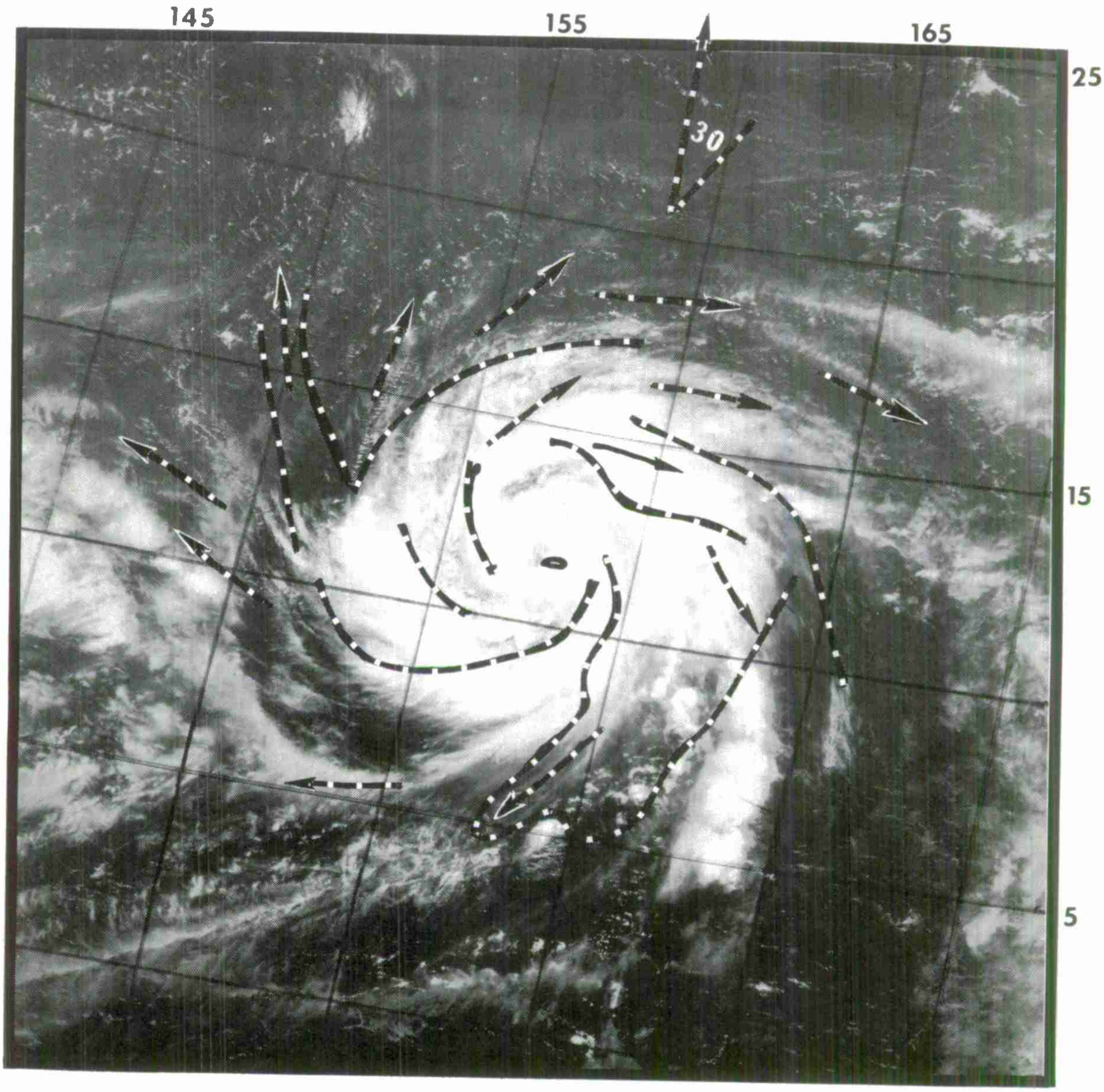

Figure 19. Typhoon Lola on 1 June 1972, 0143 GMT. Maximum surface winds - 85 kt. Arrows indicate probable direction of upper-level flow deduced from cirrus striations.

So far this paper has presented only examples of the DAPP very high resolution (VHR) visual channel of 1/3 n mi resolution. In practice, these data have been very effectively supplemented with DAPP infrared depictions (Figures 20, 21 and 22). Figure 20 is an infrared depiction of 2-n mi resolution (at sub-satellite point) to the same scale and for the same time as the VHR depiction of Lola shown in Figure 18. This depiction enhances details of the high cloud structure permitting a better estimate of upper-level flow and it also, through masking low cloudiness of small vertical development, emphasizes some of the major deep convective features of the storm -- the most important indicators of changing storm direction. This product is most successfully used in deducing storm motion in conjunction with the VHR visual product.

Figure 21 is a thresholded infrared depiction of Lola on 31 May 1972 showing storm structure in four shades of grey. Clearest areas represent the lowest level of clouds (temperatures greater than 285°k) and the darkest shade of grey shows the highest level of cloudiness (temperatures colder than 245°k). Other grey shades are indicative of intermediate level cloudiness. Such a depiction is especially useful in gaining the broadest "over-all" view (see Figure 10f). For example, the southern and western boundaries of this depiction are suggestive of the shape of an ellipse as shown. When this shape is rotated on the following day's thresholded view of Lola (Figure 22) to achieve a "best-fit", a measurement is obtained similar to that derived from the VHR product (Figure 19) which correctly called for a right turn of about 30 degrees during the following 24-hr period (see Figure 13). Thus all three products (VHR, IR and IR thresholded) supplement one another for optimum use in determining storm motion.[1]

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[1]See appendix for a condensed summary of the rules and description of the method for applying the DAPP technique.

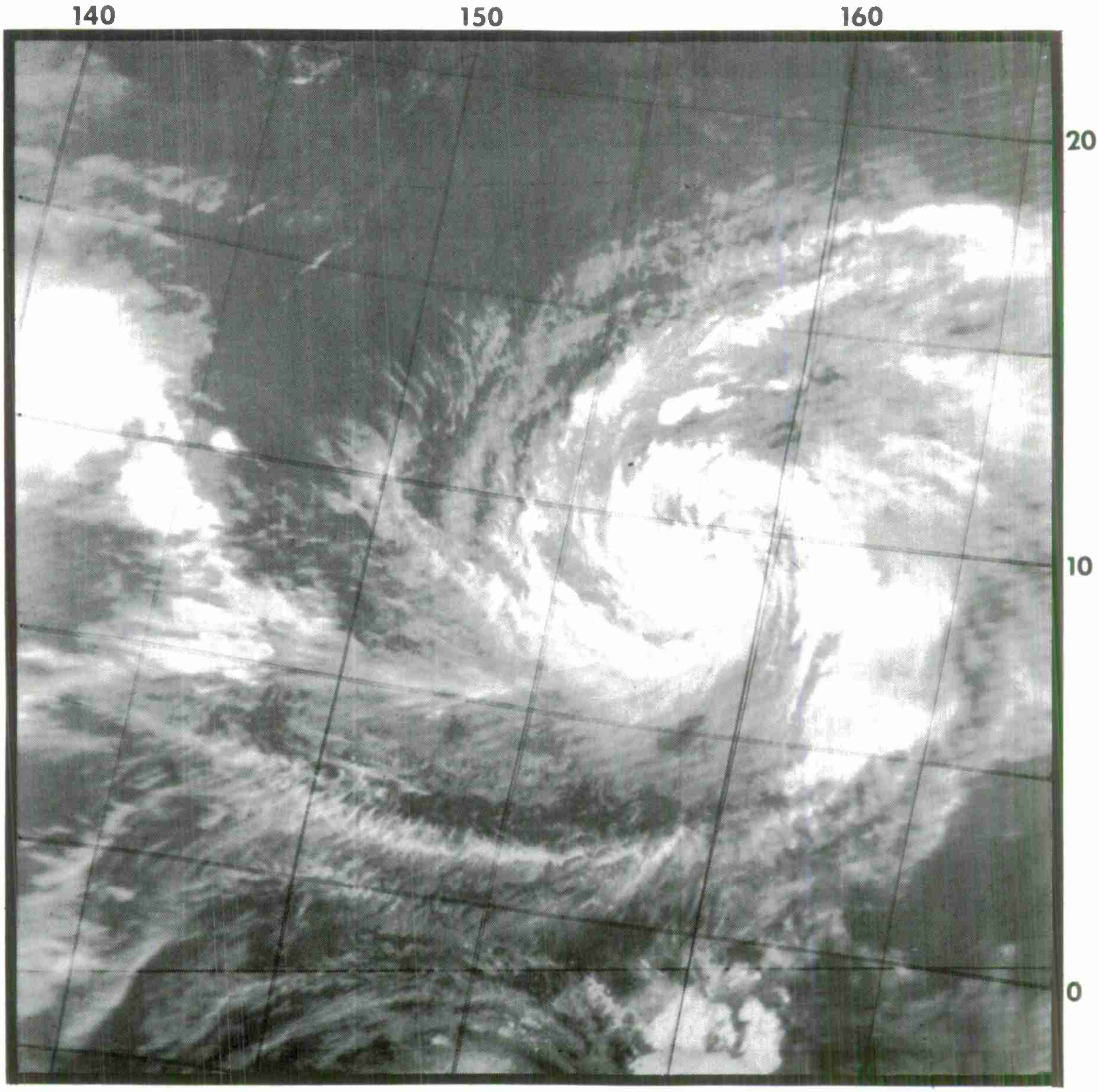

Figure 20. An infrared depiction of Tropical Storm Lola on 31 May 1972, 0158 GMT. Maximum surface winds - 60 kt. Compare this depiction with the VHR depiction of Lola in Figure 18. Note the greater amount of cirrus cloudiness shown and the isolated enhancement of major convective features.

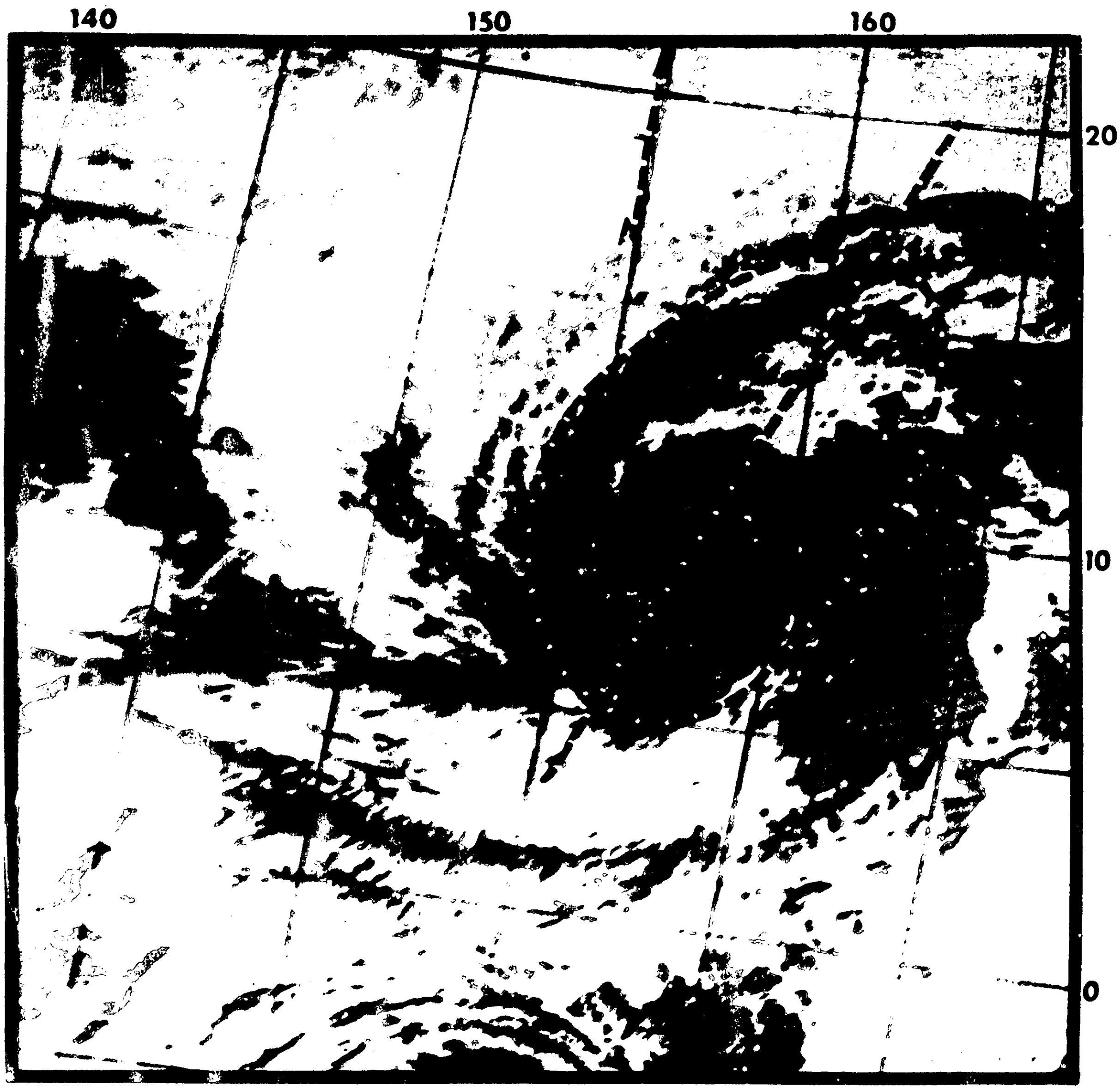

Figure 21. An infrared "thresholded" depiction of Tropical Storm Lola on 31 May 1972, 0158 GMT. Maximum surface winds - 60 kt. The darkest shade of grey indicates high clouds with temperatures colder than 245°K. Clearest areas represent the lowest level of clouds (or no clouds) with temperatures greater than 285°K. Other grey shades are indicative of intermediate level cloudiness. Compare this depiction with Figures 18 and 20.

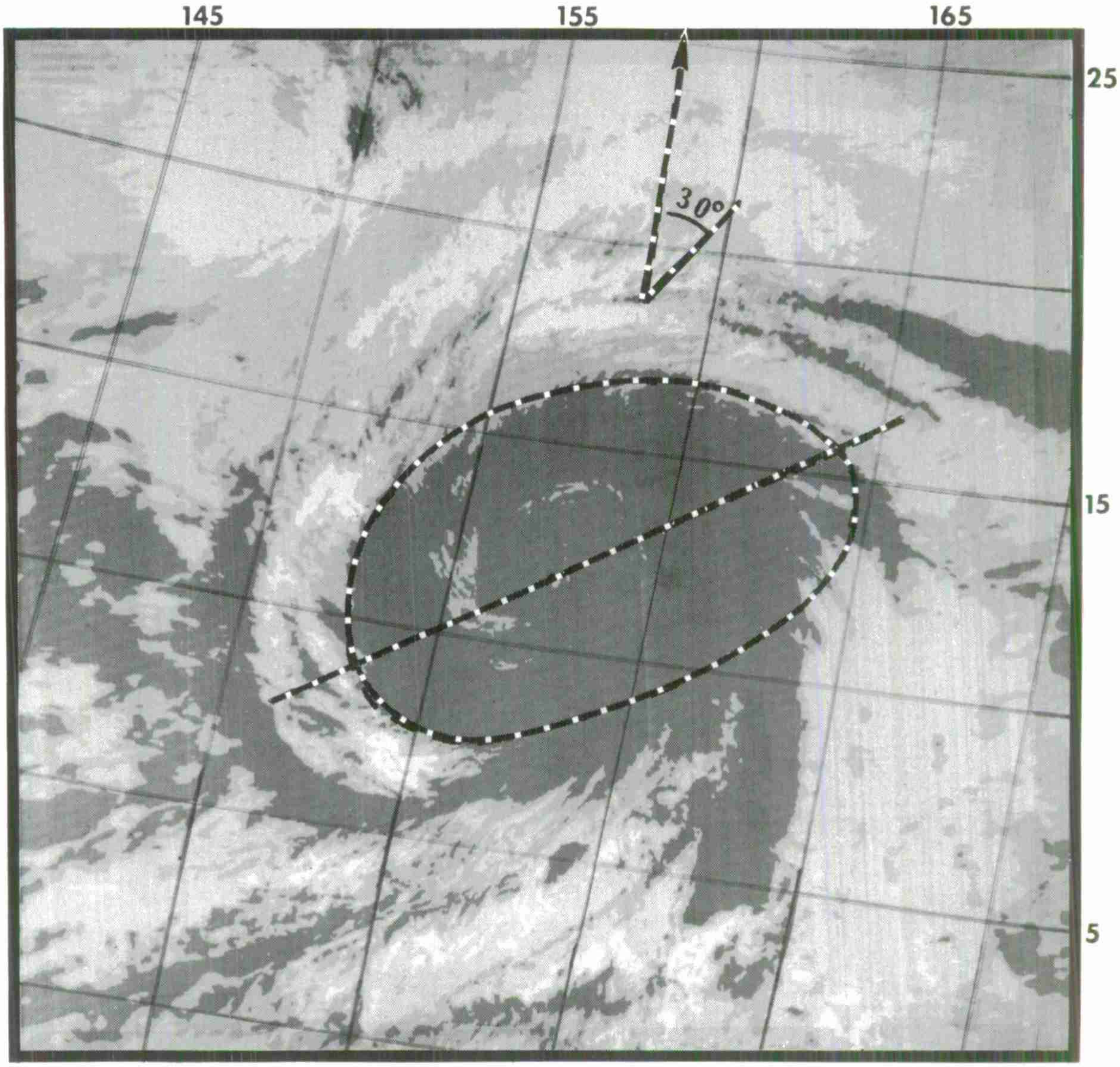

Figure 22. An infrared "thresholded" depiction of Typhoon Lola on 1 June 1972, 0143 GMT. Maximum surface winds - 85 kt. Grey shade interpretation is identical to that of Figure 21. Compare this depiction of Lola with Figure 19.

The essentials of Figure 10 (with the exception of 10e) were described to seven examinees who had no prior knowledge of the method. They attempted to test their skills against official forecasts using the methods described above and applying them to 31 separate data sets. In this preliminary test, only direction of motion forecasts were attempted, although actual position forecasts as exemplified in Figures 3-9 are clearly feasible. The results of the evaluation are described in the following section.

4. EVALUATION OF DAPP TECHNIQUE

Whenever a tropical cyclone technique is established as an aid in forecasting, it is usually compared with the Joint Typhoon Warning Center, Guam, official forecasts to determine if it can either approximate or exceed the quality of the JTWC value. Any objective forecast technique which can meet this criterion is, of course, quite valuable to the forecaster since he can incorporate the ideas and merge them into his subjective official forecast. Ideally, this would, in turn, reduce the official forecast errors.

In order to test the DAPP method of tropical cyclone movement forecasting, incorporating operationally available information, a number of assumptions and approximations were necessary in the forecast technique evaluation. These were:

(1) <u>The two satellite positions used in the evaluation extend over a period of 24 hr</u>. The average time for the 31 cases examined was 23 hr 17 min (σ [standard deviation] = 1 hr 23 min).

(2) <u>The satellite positions were approximated at 00Z for day 1 and day 2 for forecast verification purposes</u>. The second satellite pictures were in the average 122 min from the 00Z time position (σ = 55 min) for the 31 cases.

(3) <u>The satellite positions of the eye or circulation centers were located on the best track</u>.[1] During the 1972 season the DAPP satellite tropical cyclone center positions (evaluated at Detachment 1, 1st Weather Wing DAPP Site located at FWC/JTWC, Guam) averaged 24 n mi from the best track positions at corresponding times. For forecast evaluation purposes the satellite tropical cyclone centers were approximated at the best track positions. It should be noted that if an eye is present in the DAPP presentation, the deviation will be significantly

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[1] A post analysis track incorporating all available data.

lower than for a presentation with a poorly defined circulation center (approximately 15 n mi and 30 n mi, respectively).

(4) The best track position (00Z, day 2) was taken as the initial forecast or warning position.[2] The average distance the best track positions were from the actual warning positions was 20.5 n mi (σ = 19.7 n mi) for the 31 cases.

(5) All movements forecasts were verified relative to the 00Z best track position for day 3.

(6) Direction of movement was approximated as 24-hr straight line vectors between days.

Incorporating the above assumptions and approximations, 24-hr movement forecasts were made using the DAPP method for 31 tropical cyclone forecast situations for seven typhoons of the 1972 season. These movement forecasts were compared with the JTWC 24-hr movement forecasts. Figure 23 schematically shows the method of comparison for forecasts initiating at day 2 and verifying at day 3. The satellite pictures for use in the DAPP technique would be those for day 1 and day 2. Included in Figure 23 is an example which shows that, in this case, the actual direction of movement from day 1 to day 2 backed cyclonically 33° from the day 1 - 2 period to the day 2 - 3 period. The JTWC forecast would indicate a backing of 10°, while the DAPP technique would suggest a deflection of 22°. In this example, JTWC would have a 23° movement error and the DAPP method would produce an error of 11°. This type of approach was used for the 31 cases evaluated.

The answers for the DAPP technique derived by seven subjects for the 31 cases and movement errors (given in degrees error from actual values) for each of the subjects as compared to the JTWC movement error are shown in Table 1.

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[2]The warning position is the operational estimate of the position of the tropical cyclone center at the time of issuance of the forecasts.

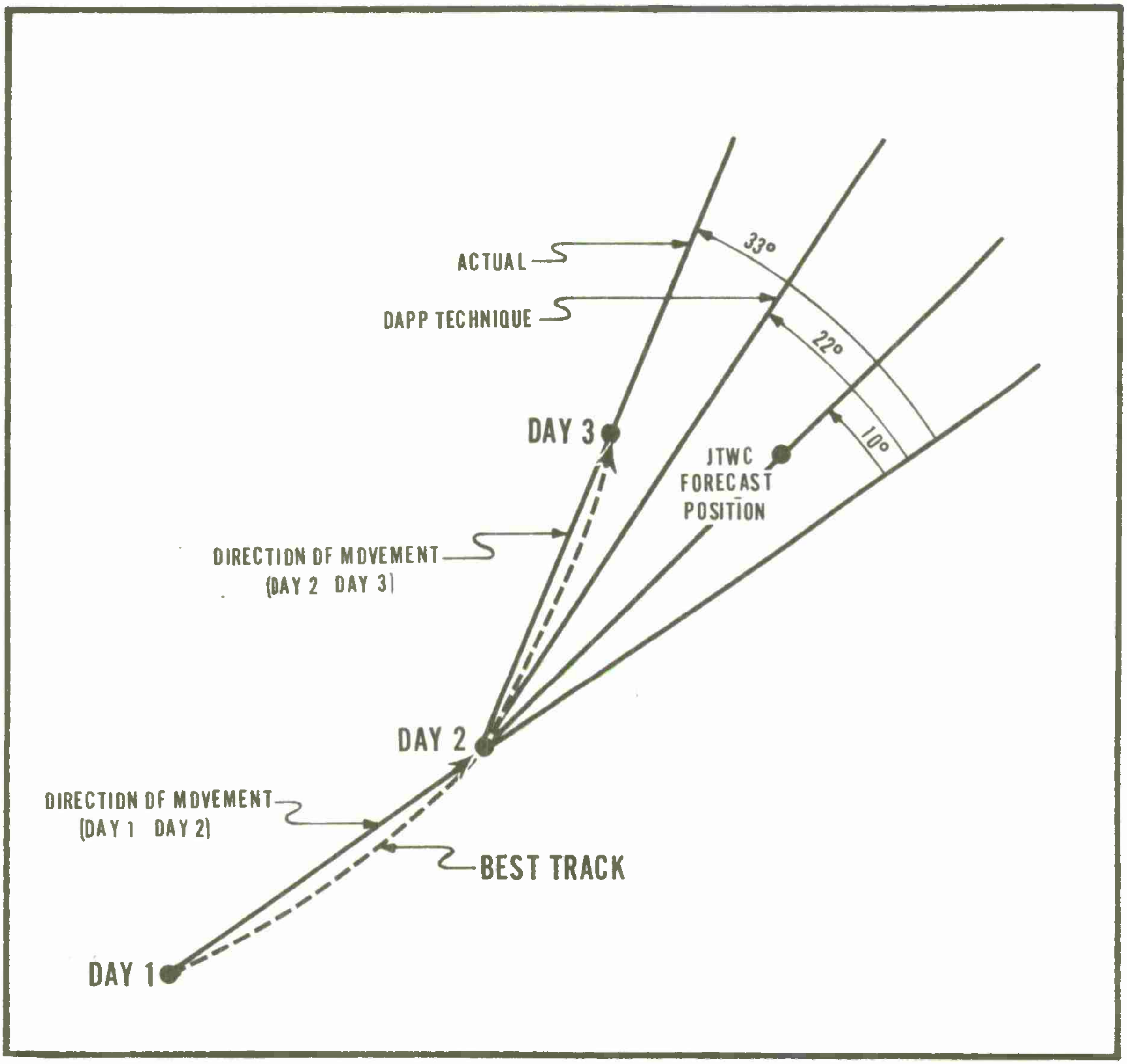

Figure 23. Schematic showing how movement forecasts were evaluated for DAPP and JTWC direction of movement forecasts versus the actual movement of the tropical cyclone. The 24-hr forecast is initiated at day 2 and verified at day 3.

Table 1. The 24-hr movement error in degrees (31 cases) for JTWC versus the 24-hr movement error for the DAPP movement technique for the seven subjects tested (A through G). The 31 cases (all from 1972 typhoons) are identified by typhoon name and by the satellite times used in the forecast technique.

CASE NO.	TYPHOON	SATELLITE TIMES	JTWC ERROR (Degrees)	DAPP TECHNIQUE ERROR (Degrees) A	B	C	D	E	F	G
1	KIT	6 JAN 0251Z/7 JAN 0235Z	25	09	15	03	01	21	19	06
2	LOLA	31 MAY 0158Z/1 JUN 0143Z	69	48	58	29	56	75	25	14
3	LOLA	1 JUN 0143Z/2 JUN 0129Z	08	51	00	106	37	106	16	57
4	LOLA	1 JUN 2210Z/2 JUN 2143Z	08	27	08	06	19	37	28	34
5	LOLA	3 JUN 0115Z/4 JUN 0100Z	32	04	17	07	32	16	03	17
6	RITA	8 JUL 0259Z/8 JUL 2208Z	21	03	03	08	02	37	26	14
7	RITA	9 JUL 0214Z/9 JUL 2322Z	03	11	08	02	08	28	02	34
8	RITA	9 JUL 2322Z/10 JUL 2254Z	03	26	17	16	02	03	02	10
9	RITA	13 JUL 0328Z/14 JUL 0313Z	12	22	27	43	12	09	77	16
10	RITA	14 JUL 0313Z/15 JUL 0259Z	110	49	143	127	85	119	131	93
11	RITA	15 JUL 0259Z/16 JUL 0244Z	59	48	32	40	42	46	32	22
12	RITA	16 JUL 0244Z/17 JUL 0230Z	25	44	01	69	29	36	44	17
13	RITA	16 JUL 2332Z/17 JUL 2305Z	164	52	23	17	06	21	31	48
14	RITA	17 JUL 2305Z/18 JUL 2238Z	50	72	89	31	82	82	42	52
15	RITA	19 JUL 0343Z/20 JUL 0328Z	42	06	27	34	16	22	13	11
16	RITA	21 JUL 0314Z/22 JUL 0259Z	55	13	54	84	25	03	50	66
17	RITA	23 JUL 2343Z/24 JUL 2316Z	15	12	60	16	02	21	17	05
18	PHYLLIS	8 JUL 2209Z/9 JUL 2140Z	75	24	22	20	02	67	12	17
19	PHYLLIS	11 JUL 0215Z/11 JUL 2228Z	17	06	28	22	18	29	13	26
20	TESS	13 JUL 2313Z/14 JUL 2105Z	49	44	34	75	54	37	84	60
21	TESS	14 JUL 0132Z/15 JUL 0117Z	53	56	17	58	49	52	37	58
22	TESS	15 JUL 2219Z/16 JUL 2151Z	10	19	09	55	08	25	16	12
23	TESS	19 JUL 0201Z/19 JUL 2210Z	21	27	56	16	26	36	16	82
24	ALICE	31 JUL 2146Z/01 AUG 2118Z	01	35	18	23	26	41	03	51
25	BETTY	9 AUG 2243Z/10 AUG 2215Z	37	04	13	05	06	18	09	03
26	BETTY	10 AUG 0149Z/11 AUG 0316Z	37	06	26	23	08	09	34	06
27	BETTY	10 AUG 2215Z/11 AUG 2148Z	25	01	01	25	04	17	15	32
28	BETTY	10 AUG 2329Z/12 AUG 2302Z	04	17	32	25	41	47	39	30
29	BETTY	13 AUG 0248Z/14 AUG 0232Z	15	04	20	01	23	00	02	08
30	BETTY	14 AUG 0232Z/15 AUG 0400Z	13	09	31	01	54	40	22	02
31	BETTY	14 AUG 2348Z/15 AUG 2320Z	01	08	04	17	21	19	06	30
		MEAN	34.2°	24.4°	28.8°	32.4°	25.7°	36.1°	27.9°	30.1°

As can be seen for the 31 cases evaluated and compared, the DAPP method produced excellent results with only one subject failing to improve on the official JTWC forecast. The average of all the scores obtained by the test participants was significantly better than the JTWC value (t-test of significance at the 5% level)[3] indicating that even for this small sample the DAPP method could be of value to the tropical cyclone forecaster.

[3] $t=\frac{\bar{x}-\mu}{s}\sqrt{N}$, where $\bar{x}$ and s is the sample mean and standard deviation, 29.3 and 4.0, respectively. The Sample consisted of the seven values in Table 1 for the seven subjects. μ is the JTWC average value (34.2) and N was taken as 7.

5. SOME ADDITIONAL CONSIDERATIONS

The DAPP method for predicting the movement of tropical cyclones, as described in section 3, is dependent essentially on the changes in the major cloud features associated with the tropical cyclone. As the technique was developed and tested, some interesting observations were found that could be of value in modifying or increasing confidence in the movement forecast.

For example, if the upper-level analyses show that the storm is drifting toward a region of increased or decreased steering current speed, the movement angle derived by the DAPP method can be modified appropriately. In a constant curvature field, an increase in the steering speed field in the forecast section of the track (refer to Figure 2) should result in a larger angular movement prediction than expected. Conversely, a decrease in the speed of the steering current would have the opposite effect. Additionally, if the steering current in the forecast section of the track differs significantly in direction from that of the analysis section, this would directly affect the forecast deflection and should be applied to increase or decrease the amount of turning to be anticipated.

In most instances, tropical cyclones will exhibit some form of consistent curvature over a period of 48 hr. With this in mind, it can be hypothesized that the intermediate positional information concerning the storm center during the 24-hr period in the analysis section of the track (T_1 to T_2 of Figure 2) could be of value in the forecast section of the track (T_2 to T_3 of Figure 2). That is, if reconnaissance, radar or satellite information shows the position of the storm center of the tropical cyclone to be to the right of the straight line vector from day T_1 to T_2 at some intermediate time, the storm will probably back cyclonically

in the following 24-hr period (refer to Figure 2A). Intermediate positional information to the left in the T_1 to T_2 period would be associated with an anticyclonic movement in the forecast period of interest as in Figure 2B.

In order to test this hypothesis the 31 cases were separated into those that backed cyclonically from day 1 - day 2 to day 2 - day 3 (17 cases), and those that veered anticyclonically from day 1 - day 2 to day 2 - day 3 (13 cases).[4] The right-angle deviations from the straight-line vector from the day 1 satellite position to the day 2 satellite position, of the available fix[5] and best track positions, were averaged and the results are shown in Figure 24. It can be seen that the fix and best track positions for cyclonically moving storms tend to be, on the average, to the right of the day 1 - day 2 vector and those for anticyclonically moving storms were to the left.

The above considerations could either be used by the forecaster to subjectively modify the DAPP movement forecast or to increase confidence in the decision reached.

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[4]There was one case where there was no change in direction of movement.

[5]The determination of the position of a tropical cyclone at a precise time, generally by reconnaissance aircraft penetration of the center; or by airborne, land or ship radar; or satellite photographs.

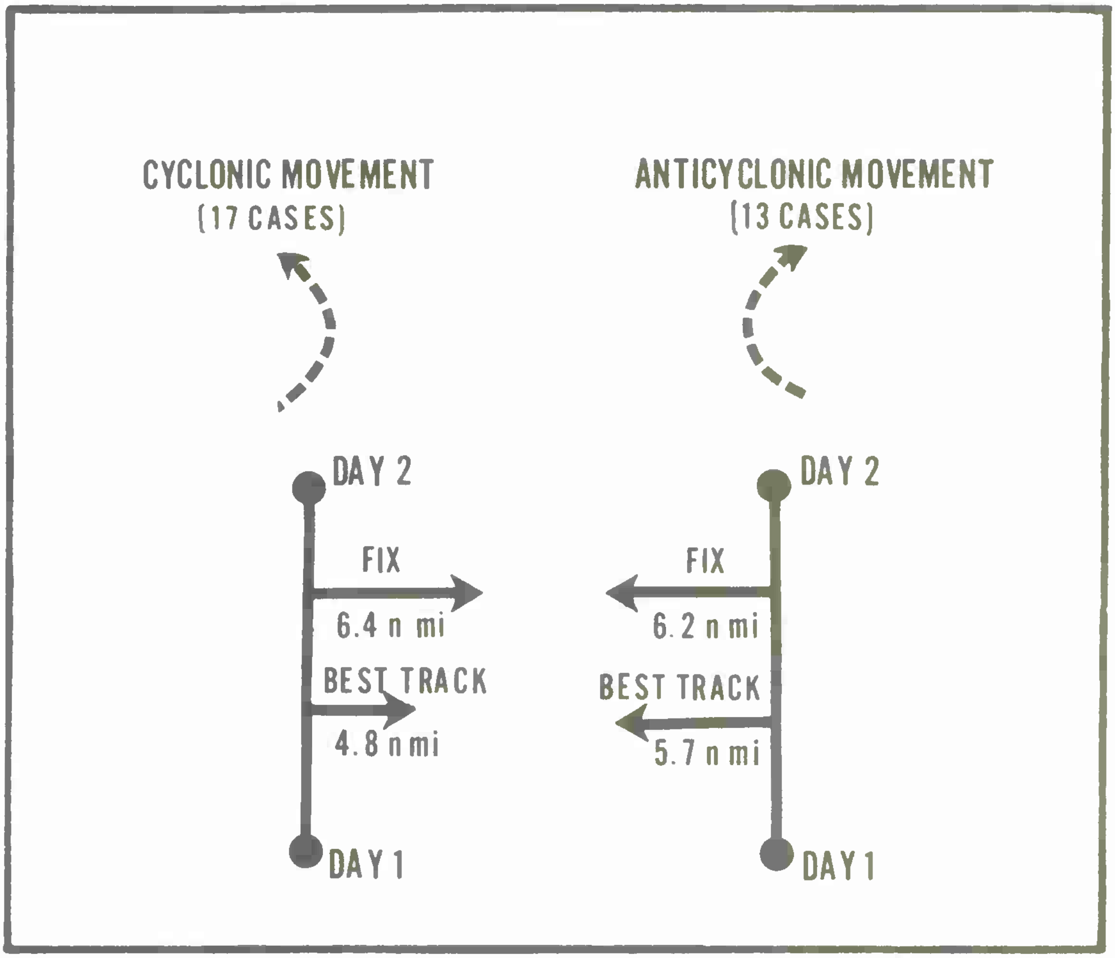

Figure 24. Average right-angle deviations of the fix and best track positions from the straight-line vector from the day 1 satellite position to the day 2 satellite position.

6. CONCLUSIONS AND DISCUSSION

The results of this initial test evaluation appear quite positive. Although the method as developed is quite subjective, computer programs based on pattern recognition or subtraction techniques to determine 24-hr rotation could be applied to quantify the approach as a "first guess." There is undoubtedly an experience or skill factor involved in applying the DAPP method successfully. Almost all test participants achieved better results with their later examples than with the first few attempts. (The test was not necessarily administered numerically as shown in Table 1). Additional tests are planned in which the examinees will have access to those operational products (surface and upper-level charts, fix positions, etc.) normally available at forecast time so that the satellite evidence can be evaluated in the total context of information available. It should again be emphasized that the unique DAPP display capabilities facilitated use of the method. Although the method should work with other satellite data, special processing, enlarging, rectifying, etc., may be necessary to optimize results.

The fact that the method is successful at all is of course significant not only from the point of view of offering hope for improving the 24-hr forecast error but from the point of view of suggesting a new approach to understanding the dynamics of the interrelationship between the storm and its environment. As stated by Malkus, et al (1961), "If in fact it turns out upon further study that there are preferred spots for tower generation which remain relatively fixed in storm coordinates, this is a significant matter. It may be related to meso-scale wind and temperature streakiness and may further hold the key to interaction between the convective structure and the large-scale dynamics of the storm."

As has been demonstrated by the examples in this paper, preferred locations for convective bands do exist which rotate, maintaining the same relative location with respect to storm movement. The upper rain and cirrus shield also rotate in a similar manner coupled with features of the underlying circulation. A rich and fertile field for further detailed investigation into this subject appears wide open.

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APPENDIX

RULES FOR APPLYING THE DAPP TECHNIQUE TO DETERMINE THE 24-HR MOVEMENT OF TROPICAL CYCLONES

A. GENERAL DESCRIPTION OF THE METHOD

Three separate depictions of the tropical cyclone are obtained daily:

(1) The VHR 1/3 n mi visual depiction.

(2) The IR 2 n mi infrared depiction. In this depiction 16 grey shades covering 100°K, each grey shade approximately 6.2°K, are displayed with a base setting of 310°K. (Recommended setting, 310°x 1 inverted, high enhance.)

(3) An IR thresholded depiction. (Recommended setting, Y_1 = 285°K, Y_2 = 265°K and Y_3 = 245°K.)

A transparent overlay is first prepared using the VHR product of the preceding day's DAPP view of the storm. This overlay shows major structural features of the storm; the eye; the outline of the dense overcast area surrounding the eye; the outline of major convective bands spiraling around the eye; the outline of cloudiness leading from the storm to other storms, and some arrows depicting the orientation of cirrus striations emanating outward from the cirrus canopy covering the storm. This overlay is oriented with respect to true north and then placed over and registered on the IR, 310 x 1 depiction. This depiction emphasizes high level cirrus striations from which additional arrows paralleling these patterns are obtained. (Basic anticyclonic, upper level outflow roughly parallel to these arrows is generally assumed.) This outline is then superimposed over the DAPP products (visual, IR and thresholded IR) of the next day. Inevitably there are some general similarities in comparing the appearance of the storm and its environment from one day to the next. This similarity is enhanced if the overlay patterns are rotated so as to

achieve a "best fit." The amount and sense of rotation required to achieve this best fit is noted.

A second overlay is prepared, tracing the 245°K contour from the IR thresholded depiction. This outline frequently defines the shape of the high cloud shield, which often assumes an elliptical pattern (see Figure 22). This overlay is oriented with respect to true north and the major axis of the ellipse, if apparent, is drawn as a dashed line. This pattern is separately rotated on the following day's thresholded view to obtain a best fit and the amount and sense of rotation noted. The separate measurements obtained by using the visual overlay and the IR thresholded overlay should agree quite closely. Variations in measurements can usually be resolved by considering all three pieces of data (VHR, IR and IR thresholded) in combination and by averaging inconsistencies. The amount and sense of rotation measured is applied as a 24-hr forecast deflection of the storm's center from its previous 24-hr straight-line track.

B. A DAPP TROPICAL CYCLONE MOVEMENT WORK SHEET

1. Products:
   a. VHR
   b. IR: (310 x 1) inverted, high enhance
   c. IR threshold: Y_1 = 285°K, Y_2 = 265°K and Y_3 = 245°K
2. Overlays (Align all with respect to true north)
   a. Visual (consider drawing the following features)
      (1) Edge of dense overcast
      (2) Eye
      (3) Clear slots
      (4) Connective clouds (cirrus or cumuliform)
      (5) Pattern emphasis (elliptical, oval, elongated, asymmetrical or comma)

(6) Arrows depicting cirrus outflow. (Obtain additional arrows from the IR 310 x 1, inverted high enhance depiction)

b. IR thresholded depiction (consider the following features)

(1) Pattern emphasis as depicted by the 245°K contour (elliptical, oval, elongated, asymmetrical or comma)

(2) Major axis of pattern

3. Rotational Comparison (rotate day 1 outline on day 2 picture according to procedures as indicated in Figure 10)

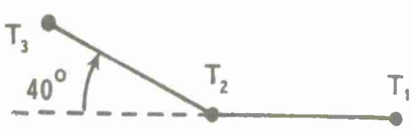
a. Location of eye on day 1 should be kept within a degree or two of location of eye on day 2.

b. Edge of main overcast area surrounding eye on day 1 should be matched with similar outline viewed on day 2. Cirrus bands and arrows indicating outflow should be used as secondary indicators for "fine-tune" adjustment.

c. Separate IR thresholded comparison should emphasize main high cloud pattern as depicted by the 245°K contour. Resolve variations of rotation required by considering all products in combination in an averaging process.

4. Deflection Measurement

a. A counterclockwise rotation of the day 1 overlay on the picture from day 2 will be indicated as minus (-) and a clockwise deflection of the overlay will be indicated as positive (+). Applied to a storm track a positive 40 degree deflection is illustrated below.



In this case if the preceding 24-hr storm track heading were, for example, 275°, we would now predict that the storm would deflect clockwise during the next 24-hr period, with an average heading during this 24-hr period of 315°.

5. Additional Considerations (refer to section 5)

a. If the upper-level analyses show that the storm is moving towards a region of increased or decreased steering current speed, the movement angle derived by the DAPP method can be modified appropriately. If the steering current in the forecast section of the track differs significantly in direction from that of the analysis section, this would directly affect the forecast deflection and should be applied to increase or decrease the amount of turning to be anticipated.

Additionally, intermediate fix positions for cyclonically curving storms tend to be to the right of the day 1 - day 2 straight-line track vector and those for anticyclonically curving storms, to the left (see Figure 24). These data should confirm the sense of rotation deduced through the overlay method described above.